Highlights from BNL and RHIC 2017

For previous years with more details see:

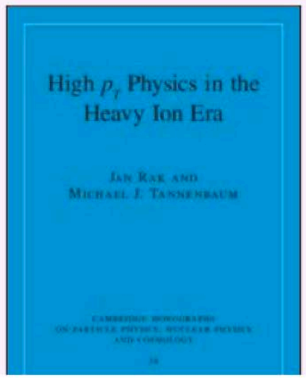
2009: IJMPA **26** (2011)5299 1406.0830

2011-2013: IJMPA **29** (2014)1430017 1406.1100

2014: arXiv1504.02771

2015: arXiv1604.08550

2016: arXiv1705.07925



High-pT Physics in the Heavy Ion Era
Jan Rak, University of Jyväskylä, Finland
Michael J. Tannenbaum, Brookhaven National Laboratory, New York

Hardback

Series: Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology(No. 34)

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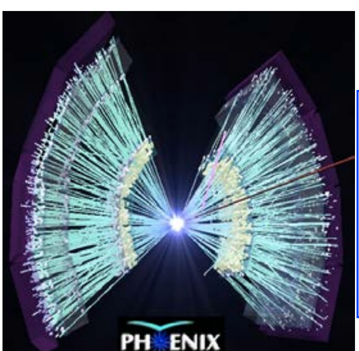
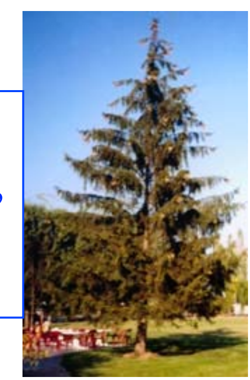
M. J. Tannenbaum
Brookhaven National Laboratory
Upton, NY 11973 USA



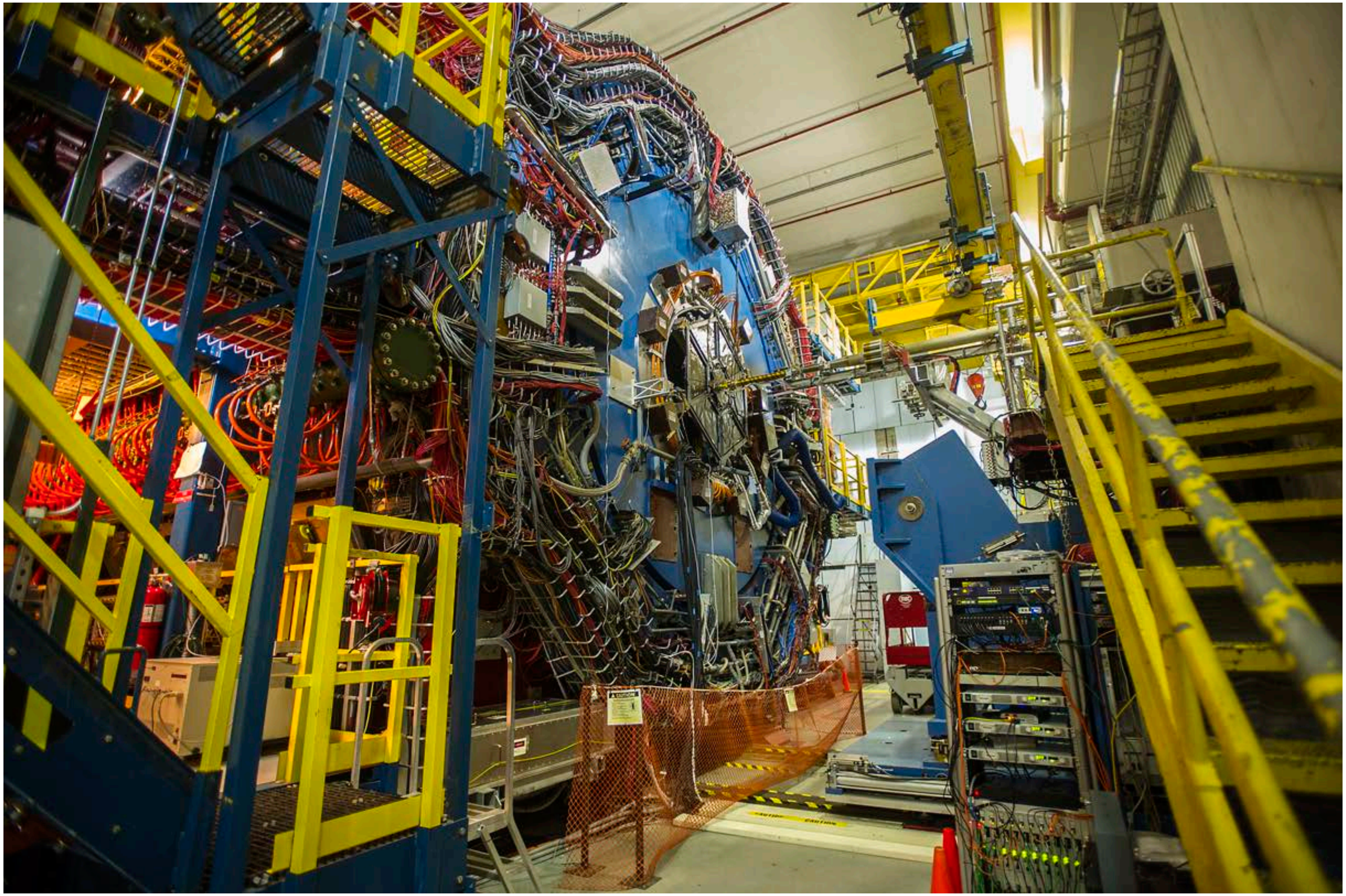
International School of Subnuclear Physics,
“Highlights from LHC and the other Frontiers of PHYSICS”
55th Course-Erice, Sicily, Italy June 14-23, 2017



The Relativistic Heavy Ion Collider (RHIC) at BNL is 1 of the 2 remaining hadron colliders and the first and only polarized p+p collider

Brookhaven National Laboratory (BNL)

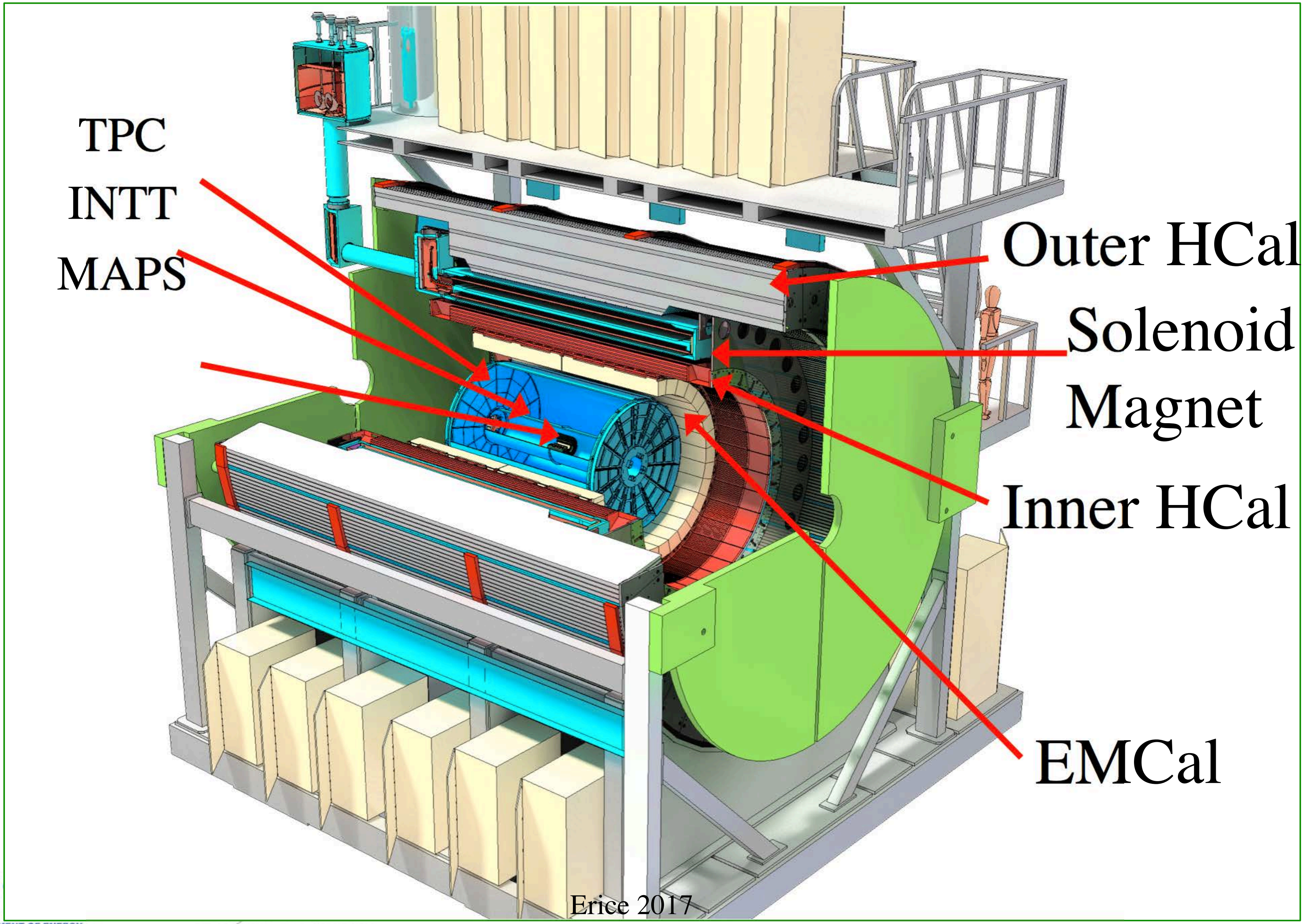
Now only one experiment at RHIC: STAR



Normal Solenoid, TPC, TOF, EMCalorimeter, VTX detctor, μ detector

PHENIX is dismantled-last run 2016

The new experiment sPHENIX is moving along well



Summary

Megan Connors

- sPHENIX obtained CD-0 and working toward next stage
  - Topical groups studying the physics goals
    - Jet Structure
    - HF Jets
    - Quarkonia
    - Cold QCD
- Tracking more defined:
  - MAPS, INTT, TPC
- Beam tests of calorimeter system
  - Calorimeter performance within sPHENIX requirements
  - Simulation reproduces the data very well
  - Publication of 2016 test beam coming soon!
  - 2017 test beam completed
- Active collaboration with lots to do:
  - https://www.facebook.com/sPHENIX.Experiment/
  - DOE CD-1 Review (week of Nov 6, 2017)
  - Looking forward to data in 2022

Biggest event this year

70 YEARS OF DISCOVERY

A CENTURY OF SERVICE

In 2017, Brookhaven Lab is celebrating two milestone anniversaries: 70 years since the Laboratory's founding in 1947 and a century since the 1917 founding of Camp Upton, the former U.S. Army base where the Lab operates today. At the same location where soldiers passed through for two world wars and Irving Berlin wrote "God Bless America," we lead and collaborate with some of the world's brightest minds—

Camp Upton 100 BNL 70 1947-1983

A Pre-presidential Visit 1948

Not-yet President of the United States Dwight D. Eisenhower visits the construction site of the Brookhaven Graphite Research Reactor.

1956

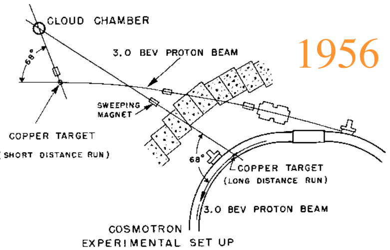
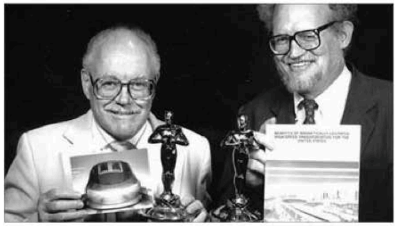


FIG. 1. Experimental arrangement, showing disposition of the beams in both the long and short distance exposures.

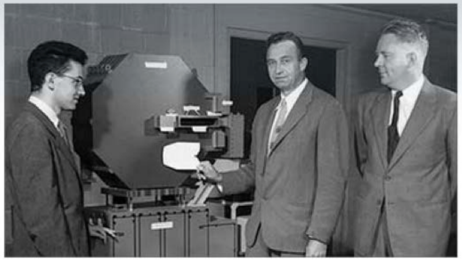
K_L discovered

1962

Nobel Prize-winning Discovery: The Muon-Neutrino

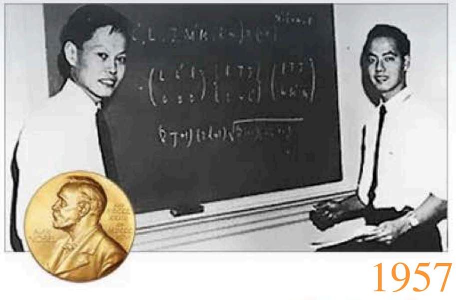


'Maglev' Patented 1968



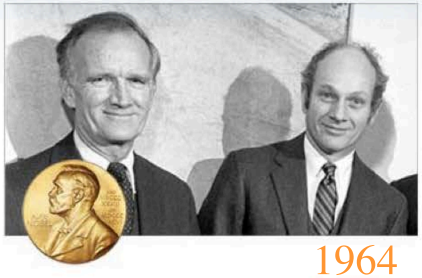
1952 **Strong Focusing**

Brookhaven physicists—including Ernst Courant and Hartland



1957

Nobel Prize-winning Discovery: Parity Violation



1964

Nobel Prize-winning Discovery: CP Violation

1974

Nobel Prize-winning Discovery: The J/Psi Particle

1953

Helicity of Neutrinos*

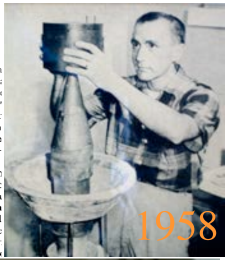
M. GOLDHABER, L. GRODZINS, AND A. W. SUNYAR

Brookhaven National Laboratory, Upton, New York

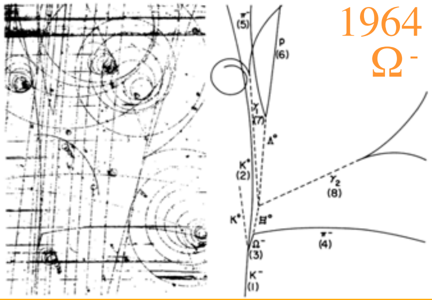
(Received December 11, 1957)

A COMBINED analysis of circular polarization an resonant scattering of γ rays following orbit electron capture measures the helicity of the neutrin We have carried out such a measurement with Eu^{152} which decays by orbital electron capture. If we assum the most plausible spin-parity assignment for th isomer compatible with its decay scheme,[1] 0−, we fin that the neutrino is "left-handed," i.e., $\sigma_\nu \cdot \hat{p}_\nu = -$ (negative helicity).

Our method may be illustrated by the followin simple example: take a nucleus A (spin $I=0$) whic decays by allowed orbital electron capture, to a excited state of a nucleus $B(I=1)$, from which a γ ra is emitted to the ground state of $B(I=0)$. The cond tions necessary for resonant scattering are best fulfille for those γ rays which are emitted opposite to th neutrino, which have an energy comparable to that



1958



1964 Ω^-

1982

NSLS Dedicated

PHYSICAL REVIEW VOLUME 96, NUMBER 1 OCTOBER 1, 1954

Conservation of Isotopic Spin and Isotopic Gauge Invariance*

C. N. YANG † AND R. L. MILLS

Brookhaven National Laboratory, Upton, New York

(Received June 28, 1954)

1954

It is pointed out that the usual principle of invariance under isotopic spin rotation is not consistant with the concept of localized fields. The possibility is explored of having invariance under local isotopic spin rotations. This leads to formulating a principle of isotopic gauge invariance and the existence of a **b** field which has the same relation to the isotopic spin that the electromagnetic field has to the electric charge. The **b** field satisfies nonlinear differential equations. The quanta of the **b** field are particles with spin unity, isotopic spin unity, and electric charge $\pm e$ or zero.

INTRODUCTION

THE conservation of isotopic spin is a much discussed concept in recent years. Historically an isotopic spin parameter was first introduced by Heisenberg[1] in 1932 to describe the two charge states (namely neutron and proton) of a nucleon. The idea that the neutron and proton correspond to two states of the same particle was suggested at that time by the fact that their masses are nearly equal, and that the light stable even nuclei contain equal numbers of them. Then in 1937 Breit, Condon, and Present pointed out the approximate equality of $p-p$ and $n-p$ interactions in the ^1S state.[2] It seemed natural to assume that this equality holds also in the other states available to both the $n-p$ and $p-p$ systems. Under such an assumption one arrives at the concept of a total isotopic spin[3] which is conserved in nucleon-nucleon interactions. Experi-

* Work performed under the auspices of the U. S. Atomic Energy Commission.

† On leave of absence from the Institute for Advanced Study, Princeton, New Jersey.

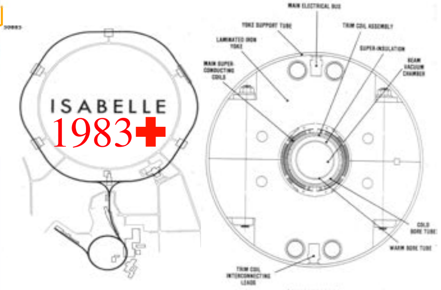
[1] W. Heisenberg, Z. Physik 77, 1 (1932).

[2] Breit, Condon, and Present, Phys. Rev. 50, 825 (1936). J. Schwinger pointed out that the small difference may be attributed to magnetic interactions [Phys. Rev. 78, 135 (1950)].

[3] The total isotopic spin T was first introduced by E. Wigner, Phys. Rev. 51, 106 (1937); B. Cassen and E. U. Condon, Phys. Rev. 50, 846 (1936).

1960

1965 **HFBR** **Third Reactor for Research**



Camp Upton 100 BNL 70 1984-2017

Volume 178, number 4 PHYSICS LETTERS B 9 October 1986

1986

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

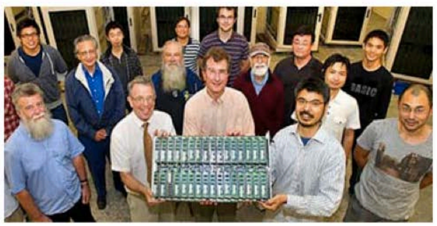
2002

Nobel Prize-winning Discovery: Cosmic Neutrinos

Data 1964-68, 1970-1994

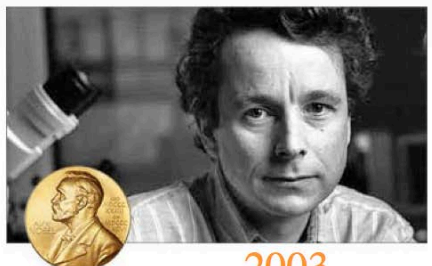
2009

Nobel Prize-winning Discovery: Atomic-Level 'Pictures' of Protein



World's Fastest Multipurpose, Non-commercial Supercomputer 1998 RBRC

The world's fastest non-commercial supercomputer makes its debut at the Japanese RIKEN BNL Research Center at Brookhaven Lab. The



2003

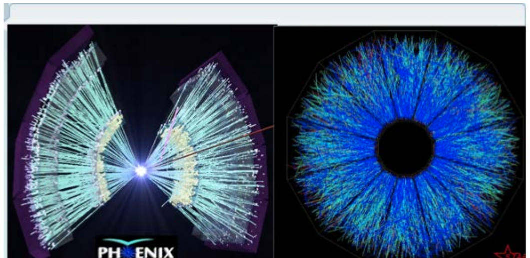
Nobel Prize-winning Discovery: Chemistry of the Cell

Roderick MacKinnon, M.D., a visiting researcher at Brookhaven

NSLS-II Opens for Science 2015

The National Synchrotron Light Source II (NSLS-II), the brightest light source of its kind in the world, is dedicated. The facility produces

2000 RHIC



The 'Perfect' Fluid sQGP 2005

Scientists discover quark-gluon plasma, a "perfect" liquid 100,000 times hotter than the center of the sun and so hot that protons and

Upgrades at BLIP Facility to Produce Radiostopes for Diagnosing, Treating Diseases

2016

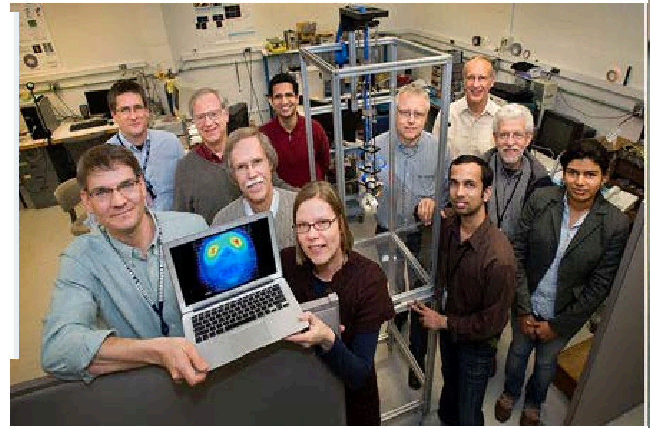
A recent Medical device development

A 'Wearable' Brain Scanner Inspired by Brookhaven Technology

Building on a Brookhaven Lab innovation designed for brain imaging in moving rats, a team in Virginia and West Virginia designs a device for studies of human interaction, dementia, movement disorders, and more

May 17, 2017

Stan Majewski, once a physicist at Jefferson Lab, now at the University of Virginia, and Julie Brefczynski-Lewis, a neuroscientist at West Virginia University—co-developers of an Ambulatory Microdose Positron Emission Tomography (AMPET) scanner—display a mockup of their device at a scientific conference. AMPET is based on a smaller mobile scanner designed for studies in rats that was developed at Brookhaven Lab.



The Brookhaven-developed scanner, dubbed "RatCAP," made it possible to scan animals without anesthesia. Members of the RatCAP team in 2011 showing a brain scan and the apparatus holding the ring-shaped detector: (front row, from left) Paul Vaska, Craig Woody, Daniela Schulz, Srilalan Krishnamoorthy, Bosky Ravindranath, (back row, from left) Sean Stoll, David Schlyer, Sri Harsha Maramraju, Martin Purschke, Fritz Henn, and Paul O'Connor.

+ ENLARGE

Nora Volkow, who led a world-renowned brain-imaging program at Brookhaven Lab, came up with the idea for RatCAP. She is now the director of the National Institute on Drug Abuse.

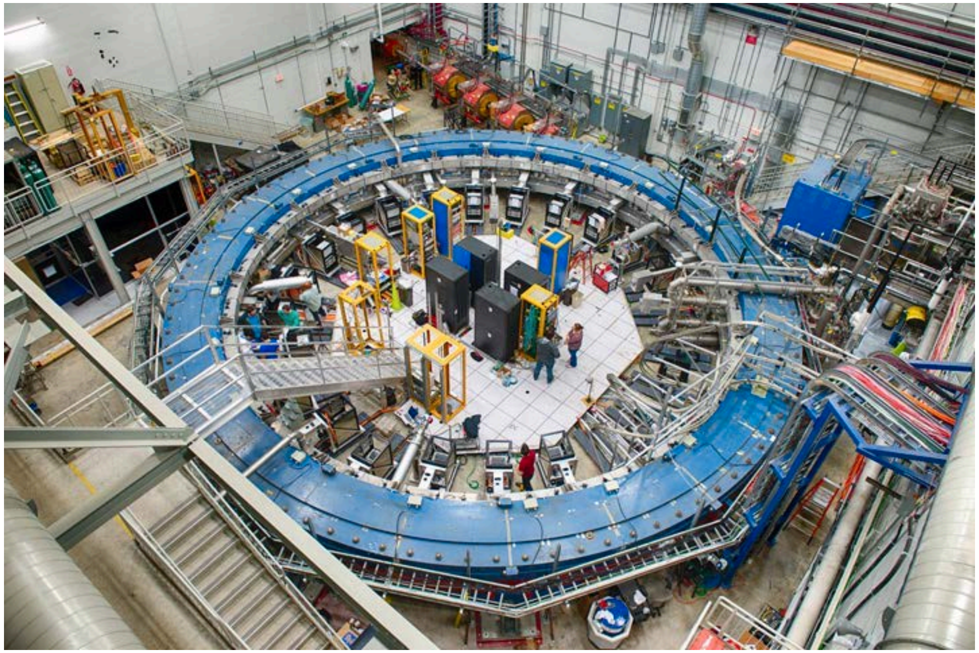
> PET scanners, as well as CT and MRI , are used by doctors but they are built by detector physicists.
>
> — Brookhaven Lab physicist Craig Woody

g-2 start at Fermilab-press release

Muon Magnet's Moment has Arrived

The Muon g-2 experiment has begun its search for phantom particles with its world-famous and well-traveled electromagnet

June 1, 2017



The Muon g-2 ring with instrumentation, awaiting muons at Fermi National Accelerator Laboratory. Credit: Fermilab

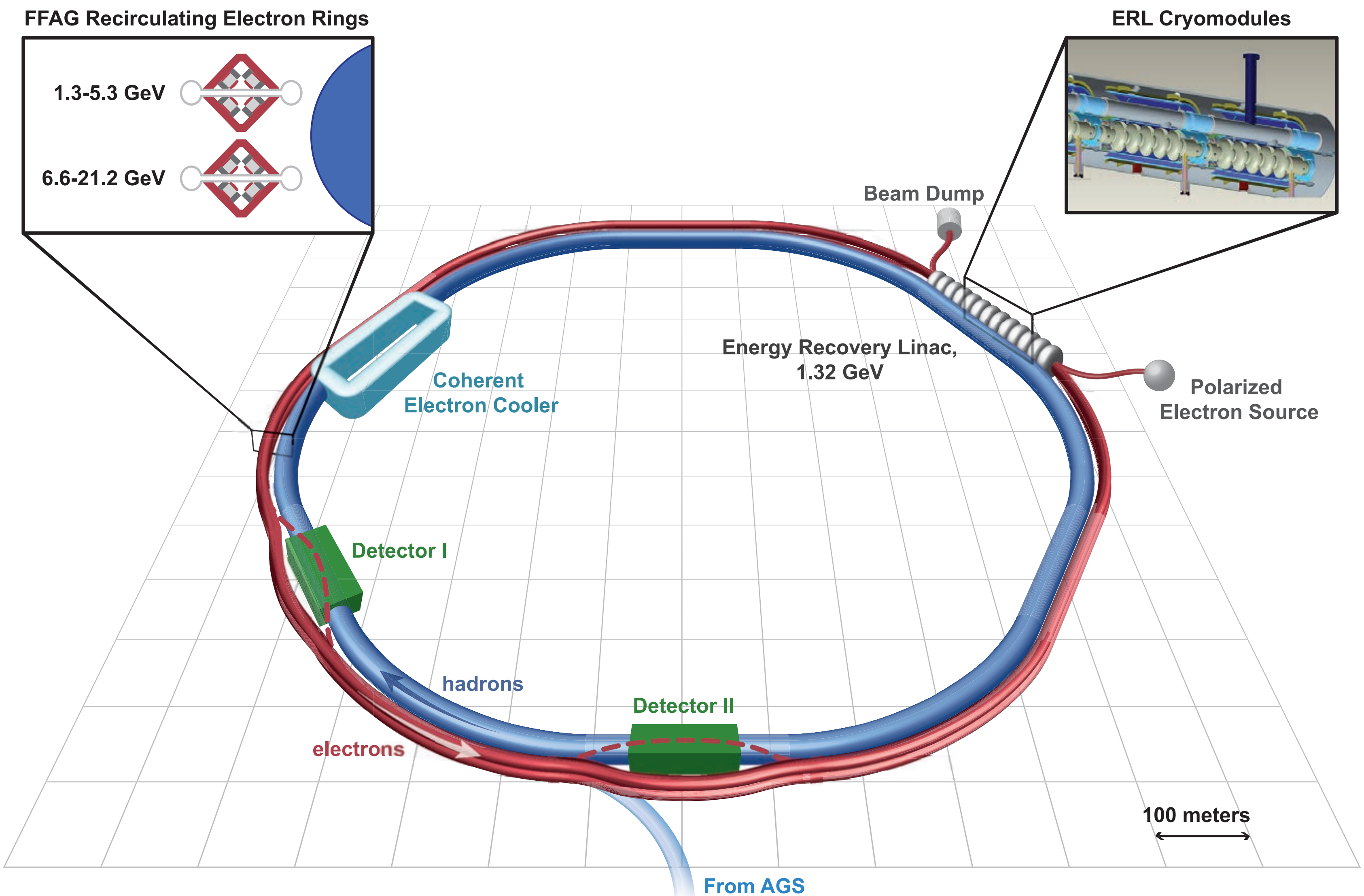
+ENLARGE

Getting to this point was a long road for Muon g-2, both figuratively and literally. The first generation of this experiment took place at the U.S. DOE's Brookhaven National Laboratory in New York State in the late 1990s and early 2000s. !!!??

Since it would have cost 10 times more to build a completely new machine at Brookhaven rather than move the magnet to Fermilab, the Muon g-2 team transported that large, fragile superconducting magnet in one piece from Long Island to the suburbs of Chicago in the summer of 2013.

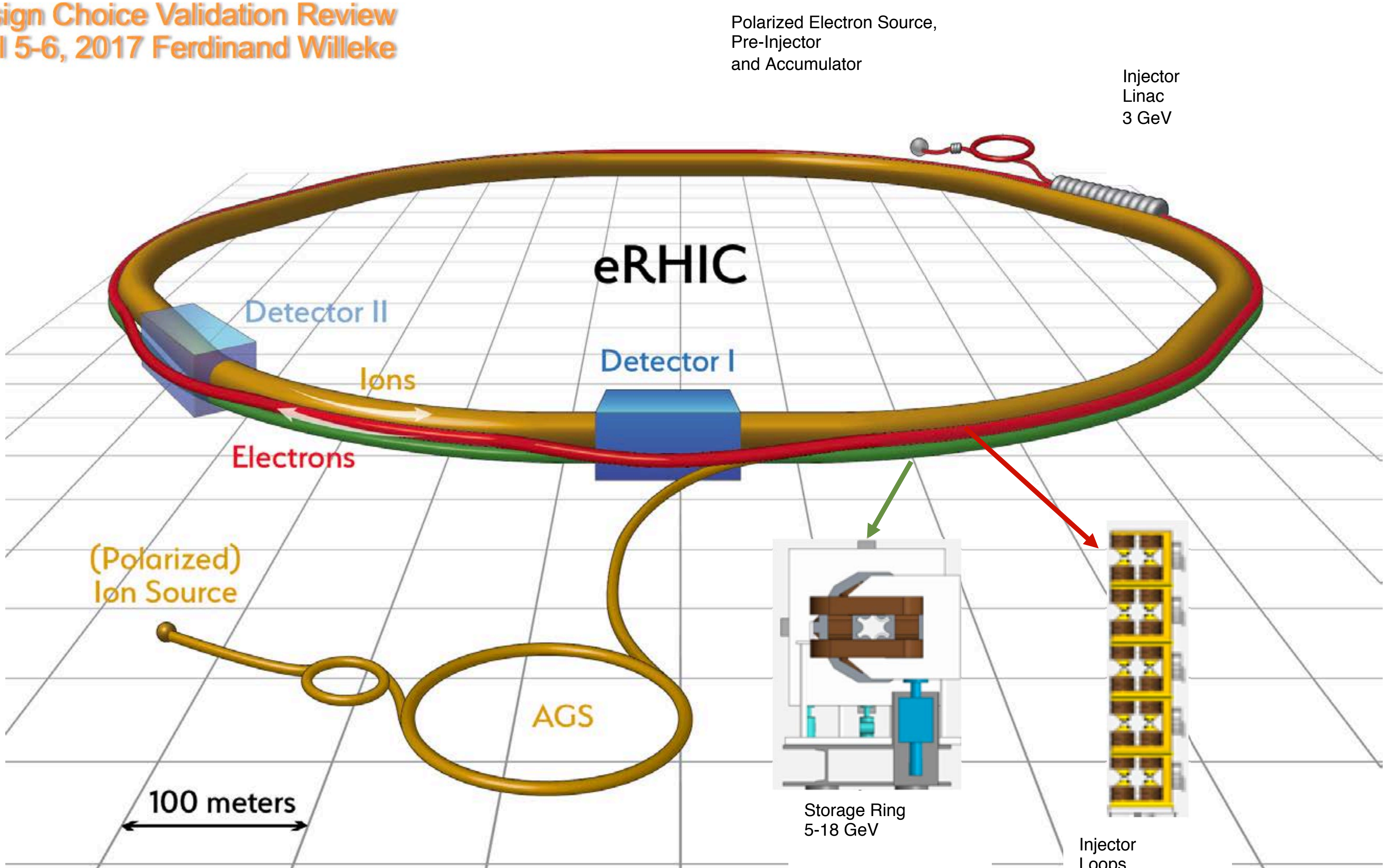
Meanwhile, back at BNL

eRHIC first design—(ISSP2014)



eRHIC design progress 2017

Design Choice Validation Review
April 5-6, 2017 Ferdinand Willeke



National Academy of Sciences: US based electron ion collider Science Assessment 2/1/17-7/31/18
http://www8.nationalacademies.org/cp/projectview.aspx?key=49811

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INFN Istituto Nazionale di Fisica Nucleare

Electron Ion Collider User Group Meeting 2017

18-22 July 2017
Europe/Rome timezone

Overview

Registration
- Registration Form

Call for Abstracts
- View my abstracts
- Submit a new abstract

Committees

Parallel Session Conveners

Draft Timetable

List of registrants

Previous Meetings

Venue

Network access

Welcome to the webpage of the Electron Ion Collider User Group Meeting 2017, which will take place in Trieste (Italy), on July 18- 22, 2017.

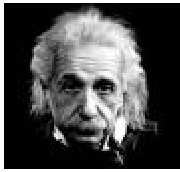
The Electron Ion Collider User Group Meeting will take place on Wednesday July 19th through Saturday July 22th, 2017 on the University of Trieste organized by the Trieste Division of INFN and the University of Trieste. It will be preceded on Tuesday July 18th by a Workshop on Accelerators dedicated to the discussion of the challenges for such a collider with European experts.

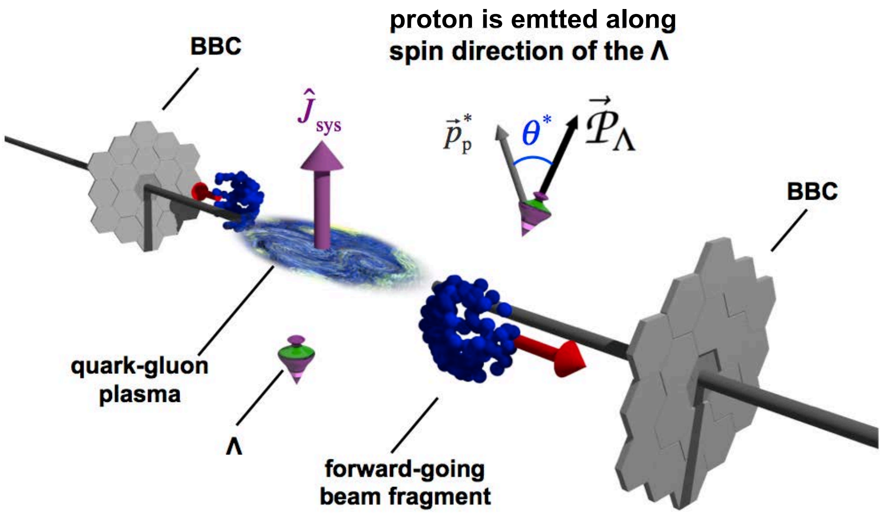
The Electron Ion Collider (EIC) is a proposed facility to study hadron physics at high energy recommended by the 2015 Long Range Plane for Nuclear Science by the NSAC. The EIC User Group (EICUG) promotes the realization of the EIC and its science and, presently it is formed by almost 700 scientists.
The motivations to hold the meeting in Europe, and in particular in Italy, are several: first of all, on top of the usual scientific progress represented by all the EICUG meetings, it will offer an opportunity to the whole European nuclear physics community to learn more about EIC, it will allow the interested European physicists to be together in the right context to start forming a coherent community, possibly including numerous young scientists, and, last but not least, it will possibly contribute to the formation of a committed community within INFN itself.

The meeting will discuss the future plans for the Electron Ion Collider, review the advancements in the strengthening the physics case, and discussing the technical plans for the collider and detectors.

The Meeting will take place at the Aula Magna of the Section of Studies in Modern Languages for Interpreting and Translation, strategically situated in the heart of Trieste, a few steps from the main hotels of the town, the Central Railway Station and the connections to the air terminal.

Au+Au Vorticity: something for a plumber or Hydrodynamics theorist to love

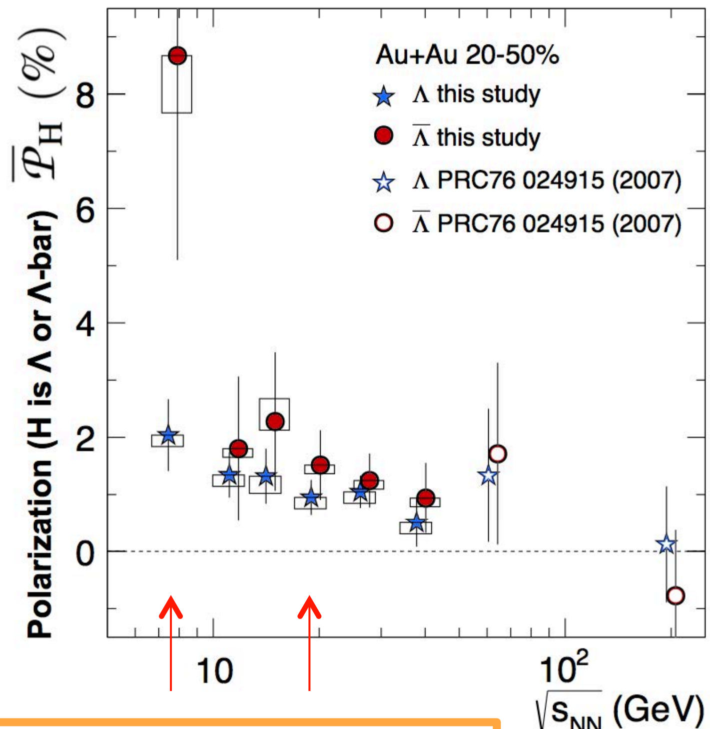




STAR-arXiv:1701.06657 to appear in Nature

Forward Λ are polarized in p+Be collision Bunce, et al PRL 36(1976)1113.
STAR claims that this effect in Au+Au is new because Λ polarization is parallel to the angular momentum of the QGP ***J**sys* everywhere

See CERN 86-07 for T.D.Lee's story of how Jack Steinberger missed parity violation of Λ decay



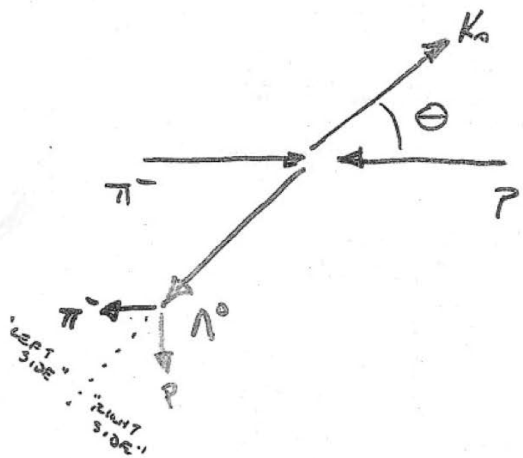
$$\omega = k_B T \left(\overline{\mathcal{P}}_{\Lambda'} + \overline{\mathcal{P}}_{\overline{\Lambda}'}\right)/\hbar$$

Vorticity Formula. See if you can get $\omega \sim 10^{22}$/s, 10^{15} times larger than any other fluid. But note, largest vorticity is at $\sqrt{s_{NN}}$=7.6--19GeV where CERN fixed target measures---is their fluid also perfect or ???

FYI for Particle Physicists

For details see
T.D.Lee CERN 86-07

IN THE CENTER-OF-MASS SYSTEM



THE QUESTION OF PARITY CONSERVATION CONCERNED THE MIRROR SYMMETRY OF THE PLANE OF THE π^-P DECAY AROUND THE Λ^0 AXIS WITH RESPECT TO A PLANE $\perp$ TO THIS PAGE (THE PRODUCTION PLANE) PASSING THROUGH THE Λ^0 AXIS. THE ANGLE $\phi = 0$ WAS DEFINED e.g. FOR π^- EMITTED UP.
IF PARITY WERE CONSERVED THERE WOULD HAVE TO BE MIRROR SYMMETRY IN THIS PLANE & ∴ THE SAME # OF π^- TO LEFT OR RIGHT;

BNL's future plan 2017

Years	Beam Species and	Science Goals	New Systems
2014	Au+Au at 15 GeV Au+Au at 200 GeV ^{3}He+Au at 200 GeV	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	p↑+p↑ at 200 GeV p↑+Au, p↑+Al at 200 GeV High statistics Au+Au ~~Au+Au at 62 GeV ?~~ d+Au @ 200, 62, 39, 20 GeV	Extract η/s(T) + constrain initial quantum fluctuations Complete heavy flavor studies Sphaleron tests Parton saturation tests	PHENIX MPC-EX STAR FMS preshower Roman Pots Coherent e-cooling test
2017	p↑+p↑ at 510 GeV	Transverse spin physics Sign change in Sivers function	Coherent e-cooling final
2018	~~No Run~~ isobars	96Zr+96Zr and 96Ru+96Ru to test chiral magnetic effect on observed Au+Au charge separation effects	Low energy e-cooling install. STAR iTPC upgrade
2019-20	Au+Au at 5-20 GeV (BES-2)	Search for QCD critical point and onset of deconfinement	Low energy e-cooling
2022-23 ~~2021-22~~	Au+Au at 200 GeV p↑+p↑, p↑+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia Forward spin & initial state physics	sPHENIX Forward upgrades ?
2024-26 ≥ 2023 ?	Factor of 10 increase Au+Au ~~No Runs~~ Factor of 4 increase p+p	Complete above measurements	Transition to eRHIC

This color is sPHENIX proposed run plan

Golden datasets of PHENIX

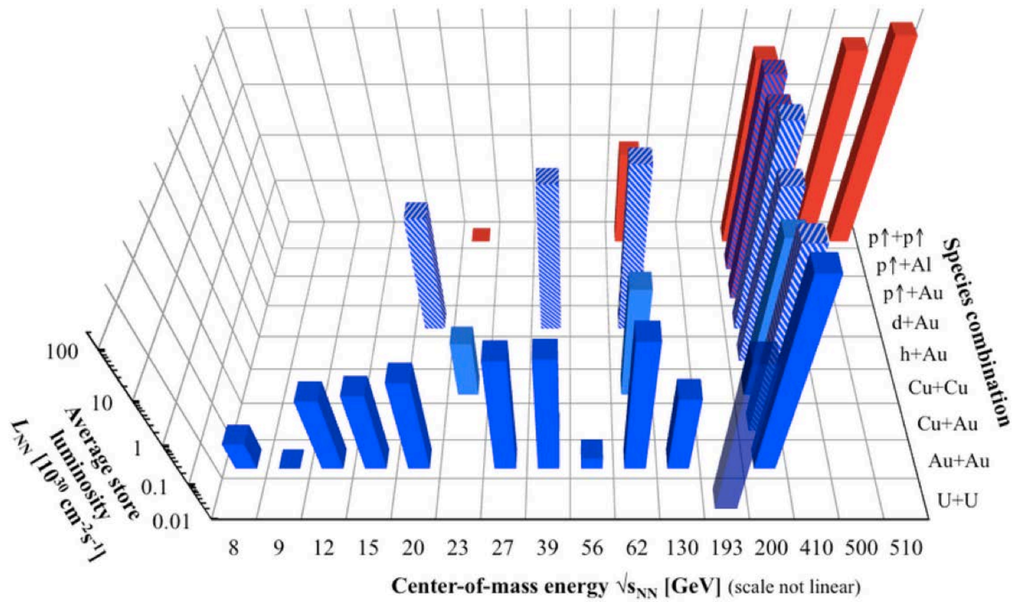
year	Beam, E(GeV)	Recorded data	upgrade	Physics
2016	AuAu 200 dAu 200 dAu 62,39,20	2.3/nb (90/pb) 1G & 73/nb 0.6G 0.1G, 8M	VTX,FVTX MPC-EX	Heavy Flavor Gluon nPDF Small QGP
2015	pp 200 pAu 200 pAl 200	23/pb 80/nb (16/pb) 275/nb (7.4/pb)	VTX, FVTX	Heavy Flavor Transverse spin CNM, small QGP
2014	AuAu 200, 15 ^{3}HeAu 200	2.3/nb (90/pb) 25/nb (15/pb)	VTX, FVTX	Heavy Flavor Small QGP
2013	pp 510	240/pb	W-trigger	Anti-quark spin Gluon spin
2012	pp 510 pp 200 CuAu 200 UU 193	50/pb 4/pb 5/nb (60/pb) 0.17/nb (10/pb)	W-trigger VTX, FVTX	Anti-quark spin Transverse spin Heavy flavor Geometry
2011	pp 510 AuAu 200 AuAu 19, 27	28/pb 0.8/nb (32/pb)	W-trigger VTX	Anti-quark spin Heavy flavor BES-I
2010	AuAu 200 AuAu 62,39,7	1.1/nb (44/pb)	HBD	Low mass ee BES-I

Many physics topics with high statistics datasets > 5 years to complete publication of all results

RHIC run History

RHIC Run	Year	Species	Energy	PHENIX Ldt
Run-1	2000	Au+Au	130 GeV	1 μb-1
Run-2	2001-2	Au+Au	200 GeV	24 μb-1
Run-2		Au+Au	19 GeV	0.4 μb-1
		p+p	200 Gev	150 nb-1
Run-3	2002/3	d+Au	200 GeV	2.74 nb-1
		p+p	200 GeV	0.35 nb-1
Run-4	2003/4	Au+Au	200 GeV	241 μb-1
		Au+Au	62.4 GeV	9 μb-1
Run-5	2005	Cu+Cu	200 GeV	3 nb-1
		Cu+Cu	62.4 GeV	0.19 nb-1
		Cu+Cu	22.4 GeV	2.7 μb-1
Run-6	2006	p+p	200 GeV	10.7 pb-1
		p+p	62.4 GeV	100 nb-1
Run-7	2007	Au+Au	200 GeV	813 μb-1
Run-8	2007/2008	d+Au	200 GeV	80 nb-1
		p+p	200 GeV	5.2 pb-1
		Au+Au	9.2 GeV	
Run-9	2009	p+p	200 GeV	16 pb-1
		p+p	500 GeV	14 pb-1
Run-10	2010	Au+Au	200 GeV	1.3 nb-1
		Au+Au	62.4 GeV	100 μb-1
		Au+Au	39 GeV	40 μb-1
		Au+Au	7.7 GeV	260 mb-1
Run-11	2011	p+p	500 GeV	27 pb-1
		Au+Au	200 GeV	915 μb-1
		Au+Au	27 GeV	5.2 μb-1
		Au+Au	19.6 GeV	13.7 M events
Run-12	2012	p+p	200 GeV	9.2 pb-1
		p+p	510 GeV	30 pb-1
		U+U	193 GeV	171 μb-1
		Cu+Au	200 GeV	4.96 nb-1
Run-13	2013	p+p (L)	510 GeV	156 pb-1
Run-14	2014	Au+Au	15 GeV	44.2 μb-1
		Au+Au	200 GeV	2.56 nb-1
		He3+Au	200 GeV	134 nb-1
Run-15	2015	p+p (L)	200 GeV	59.9 pb-1
		p+Au (T)	200 GeV	206.2 nb-1
		p+Al (T)	200 GeV	690.8 nb-1
Run-16	2016	Au+Au	200 GeV	14.3 G events
		d+Au	200 GeV	572Mcentevts
		d+Au	62.4 GeV	125Mcentevts
		d+Au	19.6 GeV	15Mcentevts
		d+Au	39 GeV	138Mcentevts
Run-17	2017	p+p (T)	510 GeV	STAR only

RHIC energies, species combinations and luminosities (Run-1 to 16)



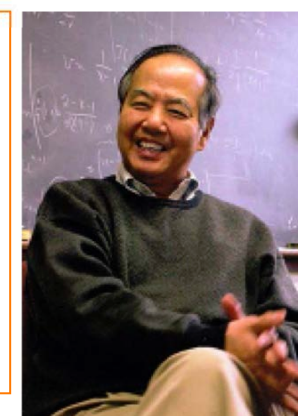
Why is 2017 RHIC run p↑+p A_N ?
What happened to A_L parity violation for W boson coupled to flavor?

Polarized Proton Physics at RHIC-started at BNL Snowmass82---approved 1995

Operation of RHIC with two beams of highly polarized protons (70%, either longitudinal or transverse) at high luminosity $\mathcal{L} = 2 \cdot 10^{32}$ cm^{-2} sec^{-1} for two months/year will allow high statistics studies of polarization phenomena in the perturbative region of hard scattering where both QCD and ElectroWeak theory make detailed predictions for polarization effects.

- **Spin Structure Functions** which require measurements in hadron collisions to complement DIS electron measurements:
  - $G(x)$ and $\Delta G(x)$ by inclusive γ and γ+Jet measurements.
  - $\Delta\bar{q}$ from Drell-Yan, $\Delta\bar{u}$ from W^-, $\Delta\bar{d}$ from W^+.

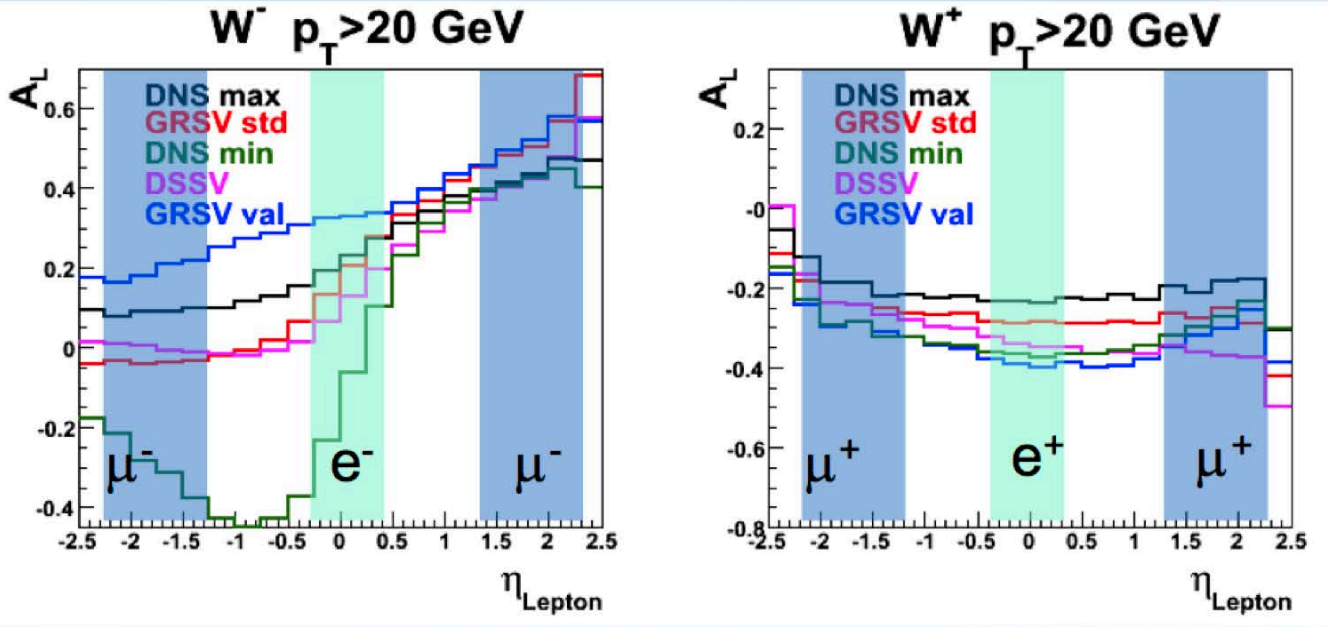
1997: To exploit spin physics and lattice gauge theory, RIKEN (Japan) provided one muon arm in PHENIX and money to support the snakes and spin rotators in RHIC. Also: the RIKEN BNL Research Center (RBRC) was established at BNL with T.D. Lee as founding Director.



Use Parity Violation of W: coupled to flavor

Sea quark polarization via W production

- Single spin asymmetry proportional to quark polarizations
- Large asymmetries
- Forward/backward separation smeared by W decay kinematics



$$\boxed{A_L = \frac{1}{P_1}\frac{\sigma^- - \sigma^+}{\sigma^- + \sigma^+}}$$

$$A_L^{W^+} \approx \frac{-\Delta u(x_1)\bar{d}(x_2)(1-\cos\theta)^2 + \Delta\bar{d}(x_1)u(x_2)(1+\cos\theta)^2}{u(x_1)\bar{d}(x_2)(1-\cos\theta)^2 + \bar{d}(x_1)u(x_2)(1+\cos\theta)^2}$$

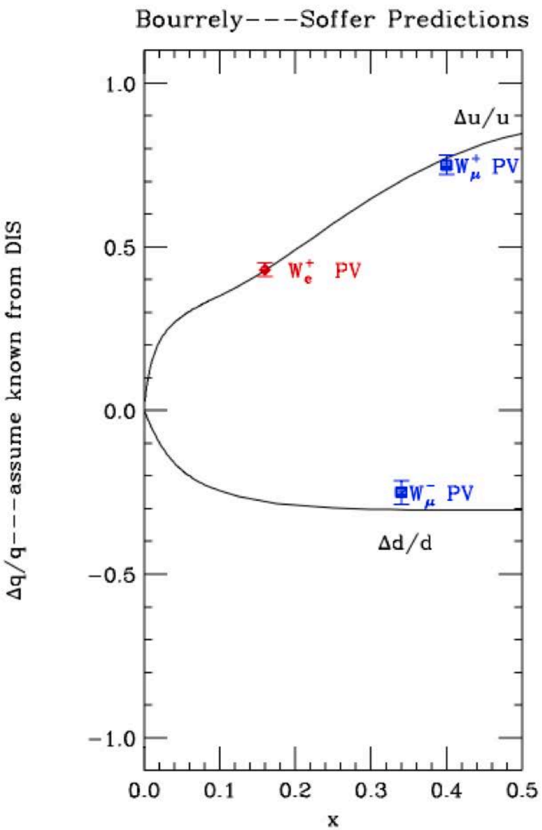
$$A_L^{W^-} \approx \frac{-\Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2 + \Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2}{d(x_1)\bar{u}(x_2)(1+\cos\theta)^2 + \bar{u}(x_1)d(x_2)(1-\cos\theta)^2}$$

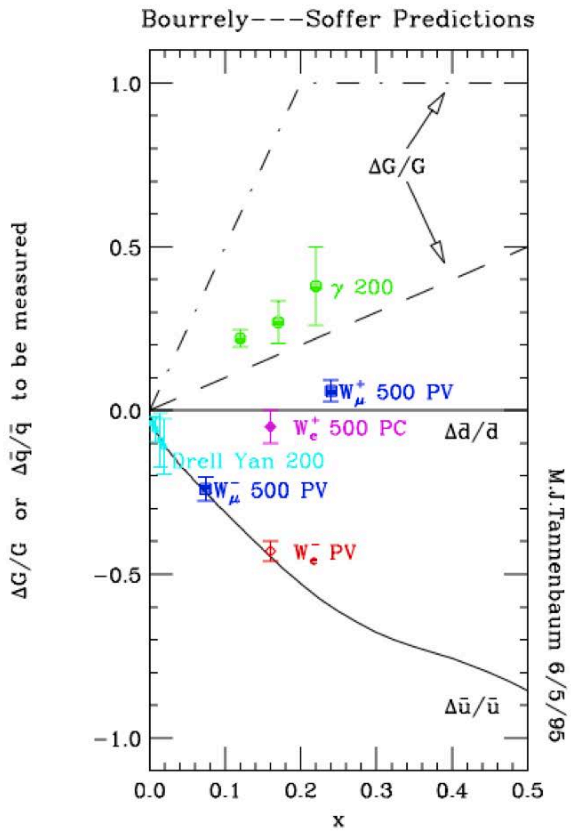
$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu_e$$
$$\bar{u} + d \rightarrow W^- \rightarrow e^- + \bar{\nu}_e$$

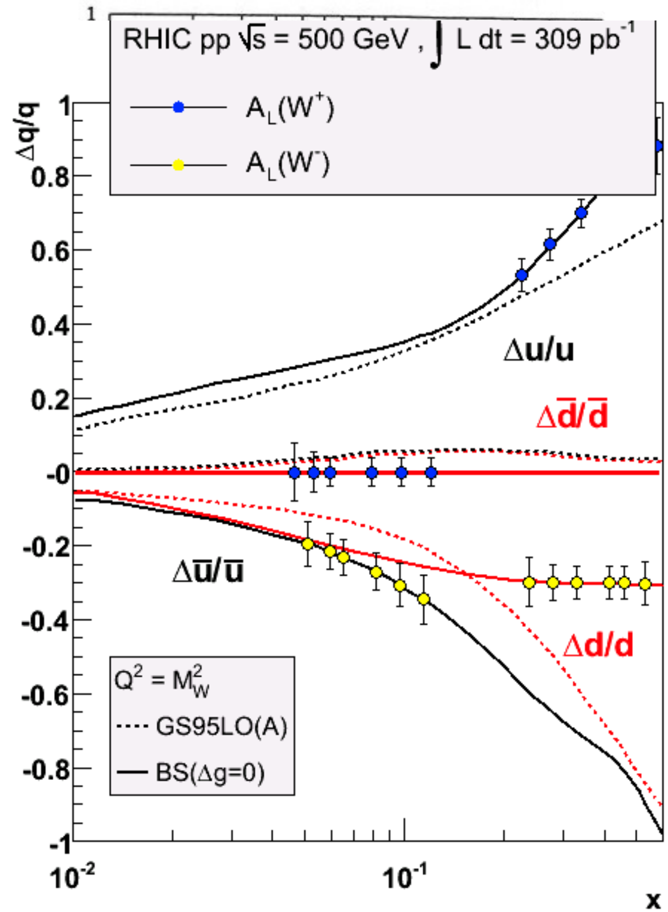
$$\langle x_1\rangle >> \langle x_2\rangle : \quad A_L^{W^-} \approx \frac{\Delta d}{d}$$
$$\langle x_1\rangle << \langle x_2\rangle : \quad A_L^{W^-} \approx \frac{\Delta \bar{u}}{\bar{u}}$$

$$\langle x_1\rangle >> \langle x_2\rangle : \quad A_L^{W^+} \approx -\frac{\Delta u}{u}$$
$$\langle x_1\rangle << \langle x_2\rangle : \quad A_L^{W^+} \approx \frac{\Delta \bar{d}}{\bar{d}}$$

Results Expected with 800 pb^{-1} at 500 GeV c.1995







mid rapidity W→e+ν

forward rapidity W→ μ +ν 1.1<|y|<2.3

We thought we could calculate LO x_1 and x_2 for p+p (q+qbar) ⇢ $W^{\pm}$+X; $W^{\pm}$ ⇢ $\mu^{\pm}$ +ν. Works well for forward μ, but more complicated than we thought---kinematic ambiguity.

Kinematic ambiguity: is y_W in the same or opposite direction as e? Missing p_T much easier

$q + \bar{q} \rightarrow W \rightarrow e + \nu$:

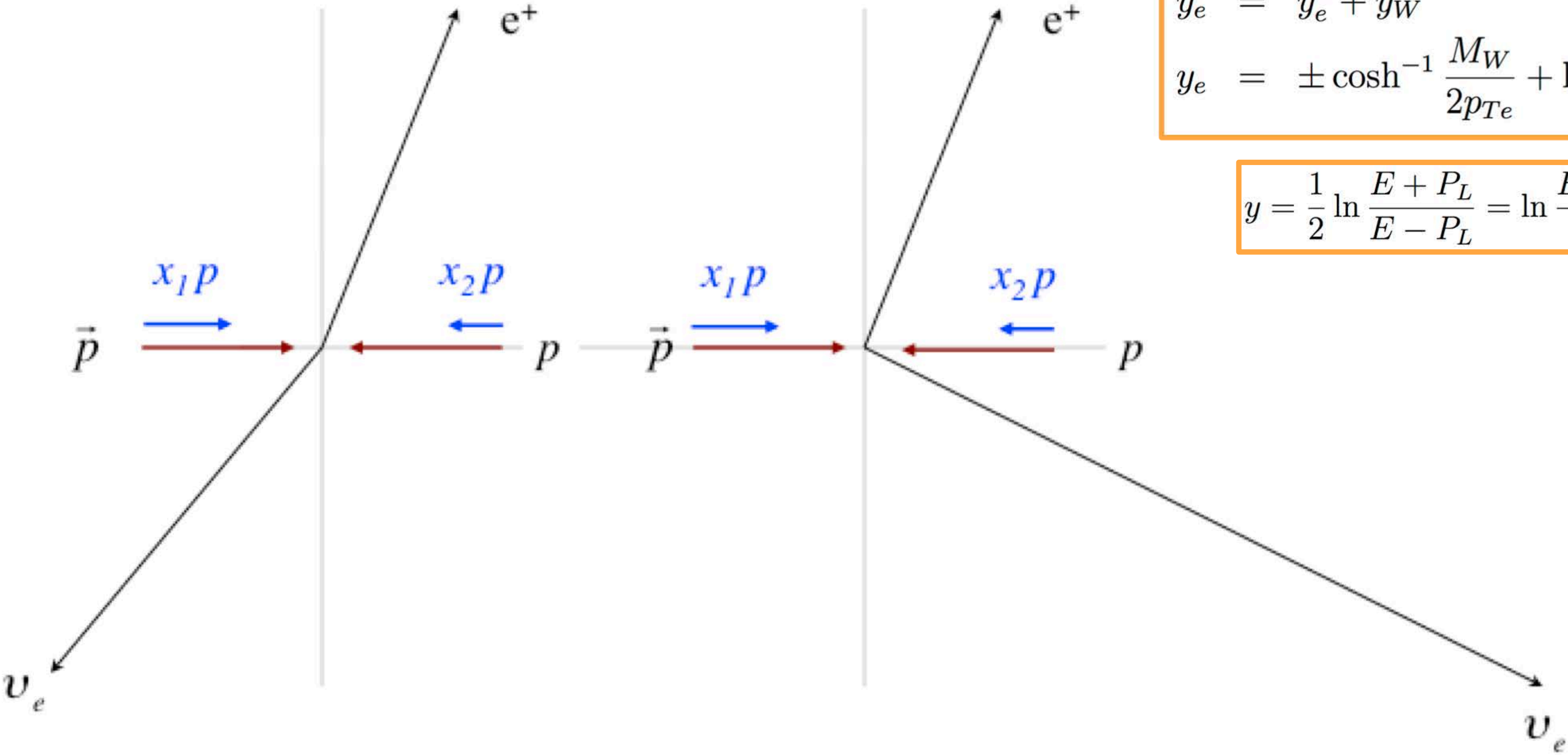
$$\hat{y} = \frac{1}{2}\ln\frac{x_1}{x_2} \qquad \hat{s} = M_W = x_1 x_2 s$$

$$\hat{y} = y_W = \ln\frac{x_1\sqrt{s}}{M_W} .$$

$$y_e = y_e^* + y_W$$

$$y_e = \pm\cosh^{-1}\frac{M_W}{2p_{Te}} + \ln\frac{x_1\sqrt{s}}{M_W}$$

$$y = \frac{1}{2}\ln\frac{E+P_L}{E-P_L} = \ln\frac{E+P_L}{m_T}$$



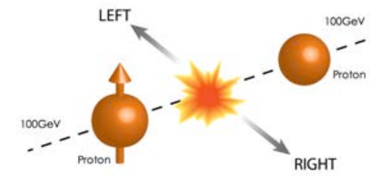
y_e=+0.35, p_T=35, y^*=+0.54, y_W=-0.19, y_ν=-0.73

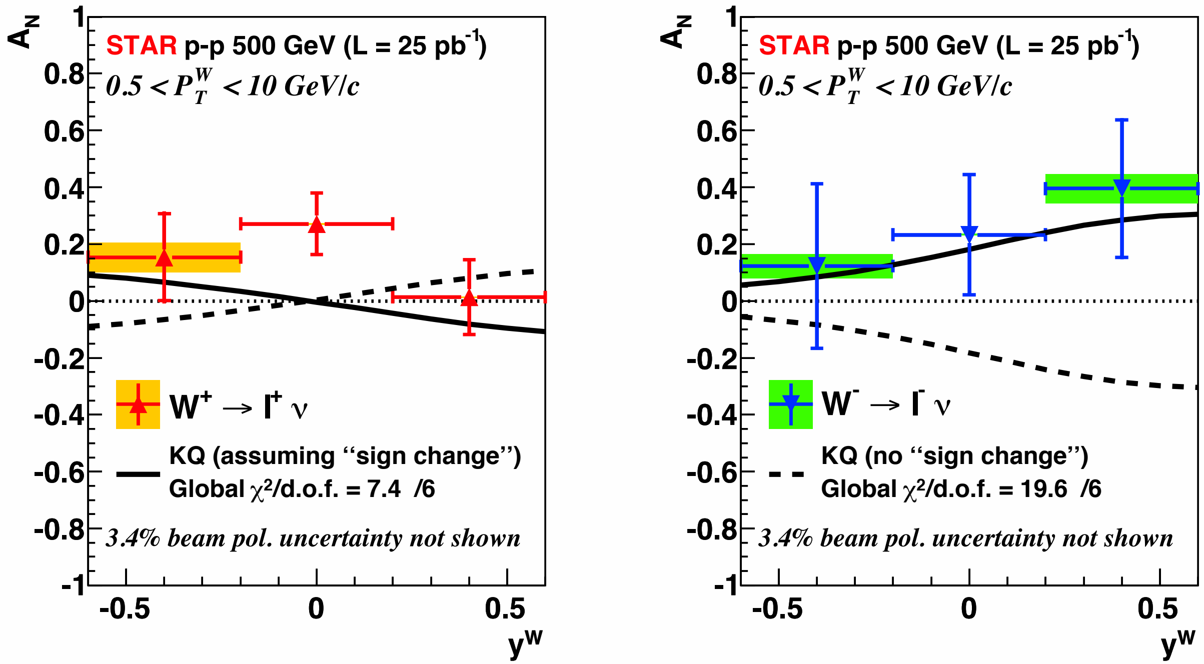
y_e=+0.35, p_T=35, y^*=-0.54, y_W=+0.89, y_ν=+1.43

STAR measurement claims to use a method from CDF to find the p_T and y_W of $W\rightarrow e+\nu$

STAR-PRL116 (2016) 132301

$$A_N = \frac{1}{\langle P \rangle} \frac{\sqrt{N_\uparrow(\phi)N_\downarrow(\phi+\pi)} - \sqrt{N_\uparrow(\phi+\pi)N_\downarrow(\phi)}}{\sqrt{N_\uparrow(\phi)N_\downarrow(\phi+\pi)} + \sqrt{N_\uparrow(\phi+\pi)N_\downarrow(\phi)}}$$





TMD is transverse momentum (k_T) dependent parton distribution functions in a proton. Sivers function is the correlation of the intrinsic k_T direction of a parton with the spin of the proton. Sivers function may change sign according to the number of gluons exchanged in the reaction, e.g. $e+p \rightarrow e+p+\pi^\pm+X$ [$\gamma+q \rightarrow \pi^\pm+X$] PRL94, 012002 compared to $q+\bar{q} \rightarrow W^\pm+X$ or $e^+ + e^- +X$. 2017 run will have >5 increase in events.

What is Sivers function and TMD factorization and who cares? U. S. President's 2018 budget gives some idea

Medium Energy Nuclear Physics:

National laboratory and university research support is reduced and several activities within the Medium Energy program are ended to enable the high priority 12 GeV JLAB science program. These include the RHIC Spin program focused on understanding the spin structure of the proton,

Heavy Ion Nuclear Physics:

Funding for operations of RHIC is provided to enable world-leading research in heavy ion nuclear physics in order to answer fundamental questions about the properties of the quark-gluon plasma discovered there and about the scientific explanation of intriguing new phenomena resulting from that discovery.
U.S. participation in the complementary CERN Large Hadron Collider (LHC) heavy ion program is ended, and national laboratory and university research is reduced.
Research efforts focus to support the domestic heavy ion program at RHIC – data taking, analysis and the enhancement of existing scientific instrumentation and infrastructure.

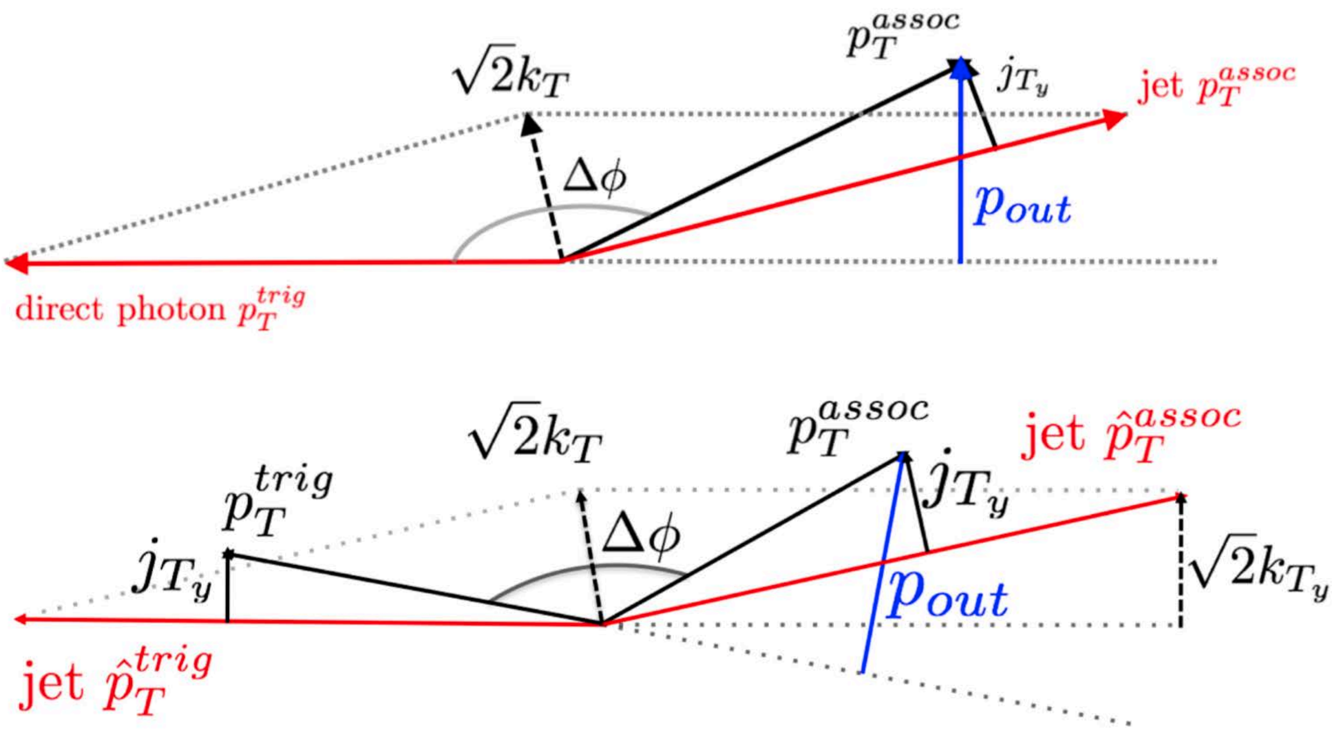
What is Sivers function and TMD factorization and who cares?

CERN COMPASS (NA58) cares, see arXiv: 1704.00488 if you like “pretzelosity”

PHENIX cares: with published and new results

What is TMD factorization and who cares?

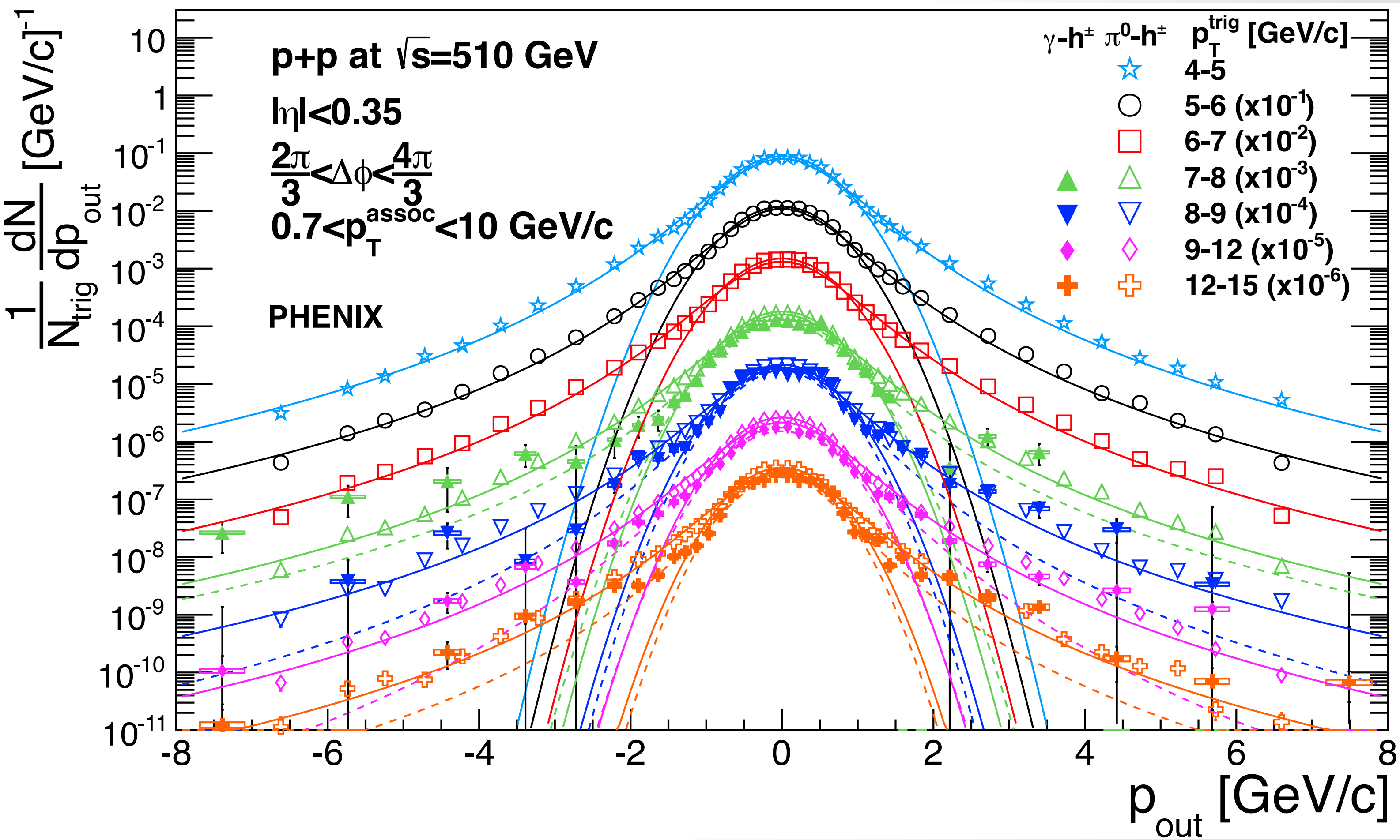
From 2016: 2 particle azimuthal correlations and k_T quark 'intrinsic' transverse momentum



Dijets and dihadrons are not back to back in azimuth because of k_T, mean parton transverse momentum in a nucleon, named by Feynman, Field and Fox NPB128,1-65

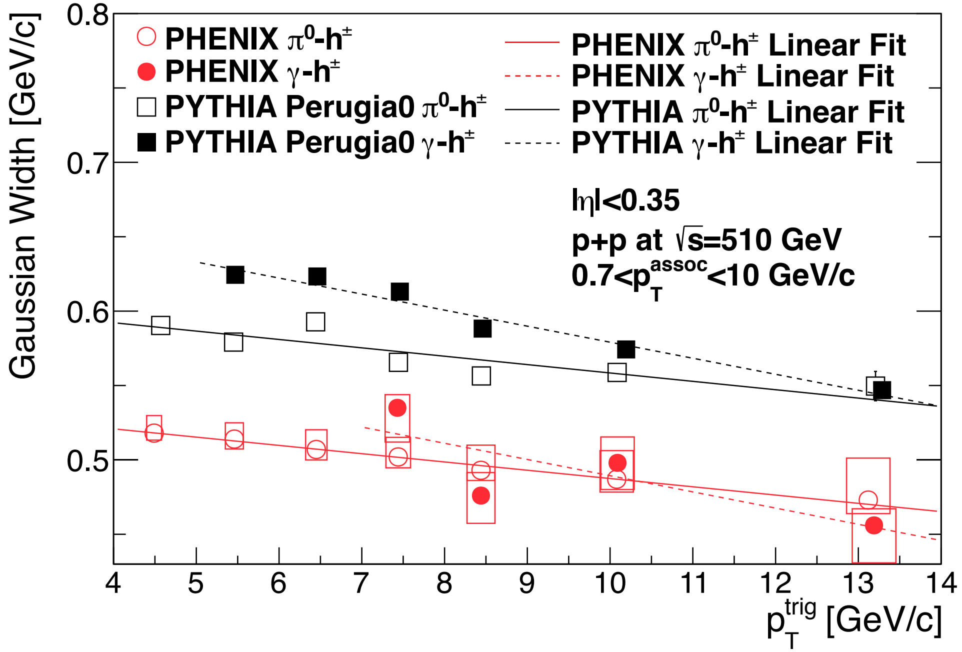
p_{out} distribution vs p_{Tt}

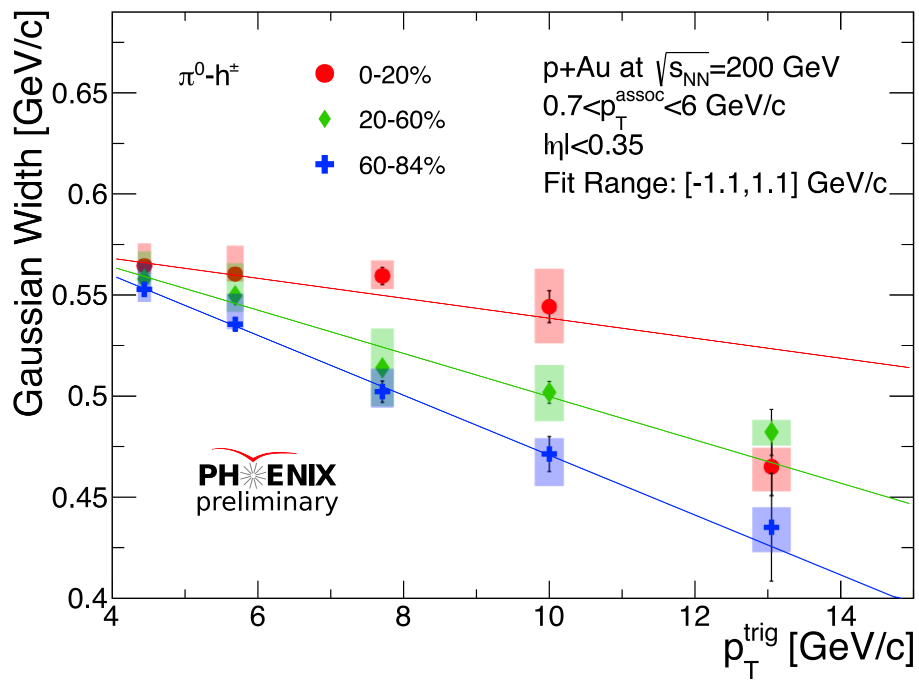
PHENIX-PRD95 (2017) 072002



Gaussian for pout<1.5 GeV/c likely represents the intrinsic k_T while the power law for pout>1.5 GeV/c is likely standard QCD gluon radiation

Gaussian width decreases with p_{Tt} for π^0-h and γ-h in p+p and π^0-h p+Au





The decrease of the Gaussian width for π^0-h with increasing hard-scale (p_{Ttrig}) is consistent with QCD (Pythia) with no TMD factorization and opposite from the TMD prediction for γ+h which should increase (see PRD95, 072002 and arXiv:1704.00488 for explanations). The increasing width with centrality in p+Au for $p_{Ttrig} \leq 10$ GeV/c but not for larger p_{Ttrig} may be relevant for azimuthal broadening predictions in A+A collisions (to be discussed later).

Factorization in LO-QCD in 1 slide

Cross Section in p-p collisions c.m. energy $\sqrt{s}$

The overall p-p reaction cross section
is the sum over constituent reactions

$$a + b \to c + d$$

$f_a^A(x_1)$, $f_b^B(x_2)$, are structure functions, the differential probabilities
for constituents a and b to carry momentum fractions x_1 and x_2
of their respective protons, e.g. $u(x_1)$,

$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{1}{s}\sum_{ab} f_a^A(x_1) f_b^B(x_2) \frac{\pi\alpha_s^2(Q^2)}{2x_1x_2}\Sigma^{ab}(\cos\theta^*)$$

$\Sigma^{ab}(\cos\theta^*)$, the characteristic subprocess angular distributions
and $\alpha_s(Q^2) = \frac{12\pi}{25\ln(Q^2/\Lambda^2)}$ are predicted by QCD

QCD cross sections factorize to structure function, subprocesses and (not shown here) fragmentation functions. Do the structure functions depend on k_T and if so do they factorize also? If so, this would be TMD factorization.

Review of RHIC "world-leading research in heavy ion nuclear physics" and answers to fundamental questions about the properties of the quark-gluon plasma discovered there

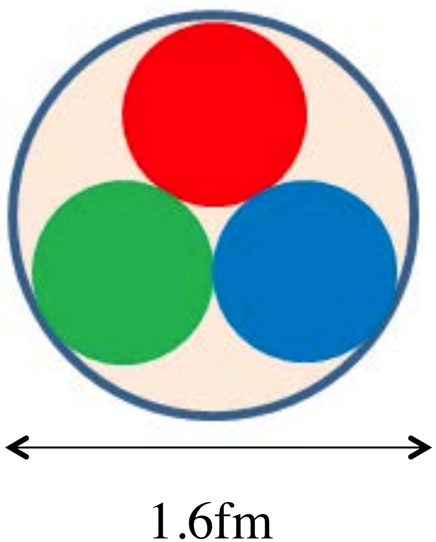
(QGP) Discoveries at RHIC

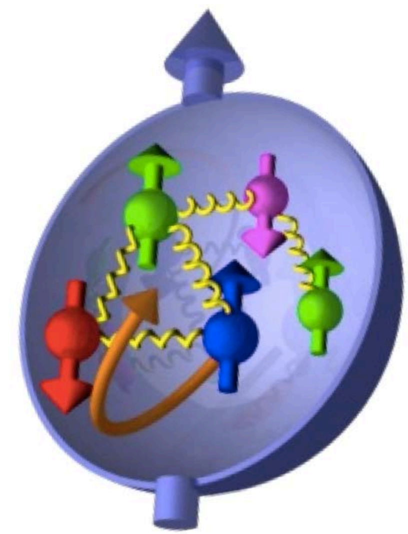
- Suppression of high p_T hadrons from hard-scattering of initial state partons; also modification of the away-side jet
- Elliptic Flow at the Hydrodynamic limit as a near ideal fluid with shear viscosity/entropy density at or near the quantum lower bound $\eta/s \approx 1/(4\pi)$
- Elliptic flow of particles proportional to the number of the valence (constituent) quark count.
- Charged particle multiplicity proportional to the number of constituent quark participants
- Higher order flow moments proportional to density fluctuations of the initial colliding nuclei
- Suppression and flow of heavy quarks roughly the same as that of light quarks; QCD hard direct photons not suppressed, don't flow.
- Production and flow of thermal soft photons.

Constituent Quarks cf. Partons

Constituent quarks are Gell-Mann's quarks from Phys. Lett. 8 (1964)214, proton=uud [Zweig's Aces].These are relevant for static properties and soft physics, low $Q^2<2$ GeV^2 ; resolution> 0.14fm

For hard-scattering, $p_T>2$ GeV/c, $Q^2=2p_T{}^2>8$ GeV^2, the partons (~massless current quarks, gluons and sea quarks) become visible



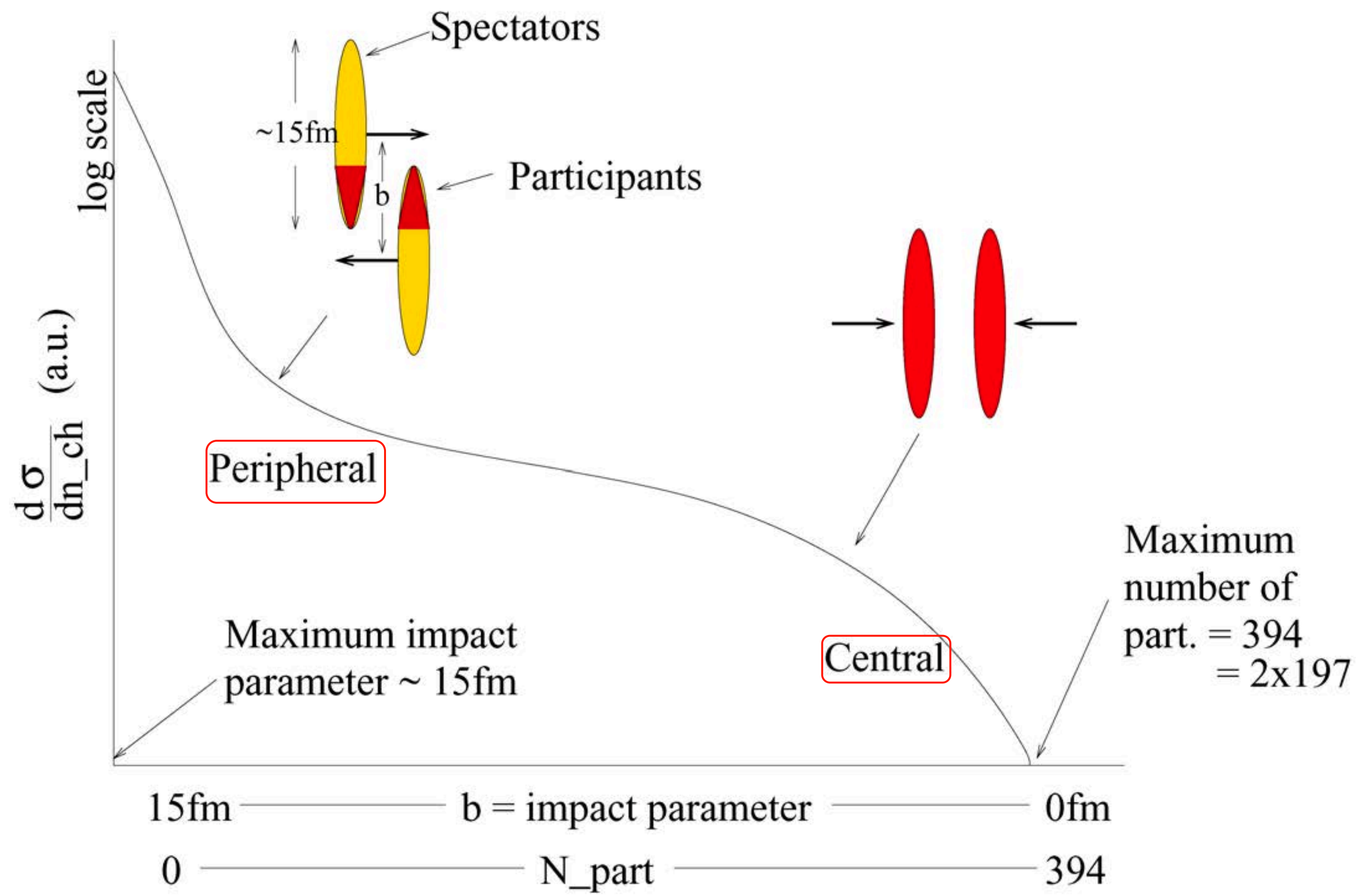


Resolution ~0.5fm

Resolution ~0.1fm

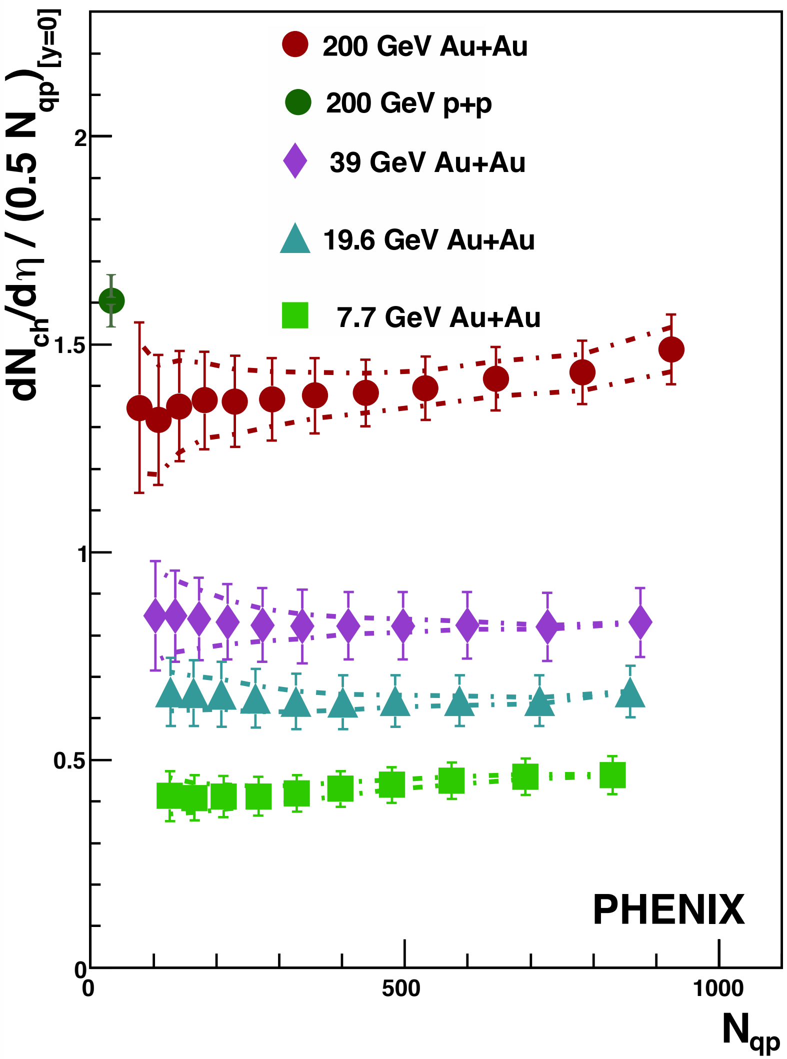
Resolution <0.07fm

Some special Issues for A+A collisions



Schematic of collision in N-N c.m. system of two Lorentz contracted nuclei with radius R and impact parameter b. The curve with ordinate $d\sigma/dn_{ch}$ represents the relative probability of charged particle multiplicity n_{ch} which is proportional to the number of participating nucleons N_{part} (actually to number of participating constituent quarks, N_{qp})The degree of overlap of the two nuclei is called the centrality. More central means smaller b.

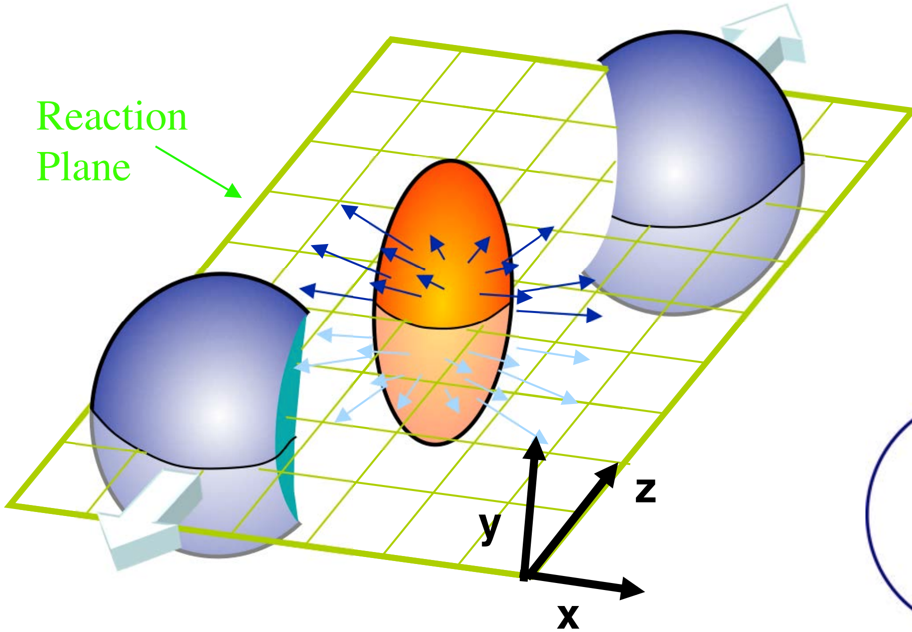
Constituent-quark-participant scaling-N_{qp}



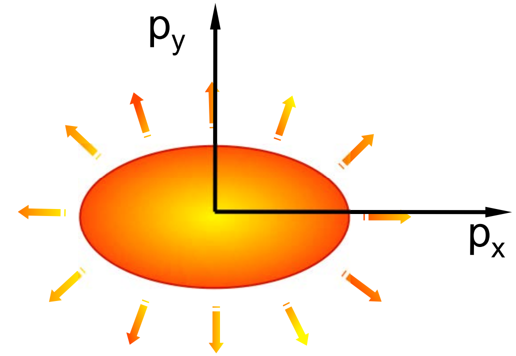
Charged particle multiplicity $dN_{ch}/d\eta$ is proportional to the the number of constituent quark participants N_{qp}

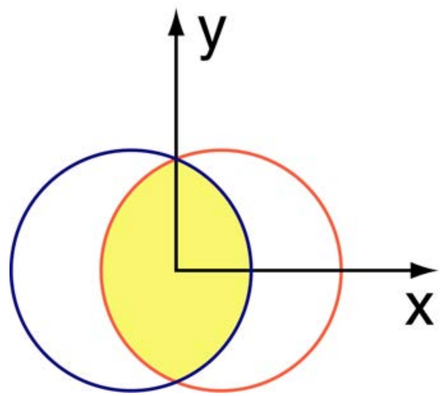
PHENIX PRC93(2016)024901

Anisotropic Transverse Flow--an Interesting complication in AA collisions



• spatial anisotropy⇒ momentum anisotropy





$$\phi = \mathrm{atan}\,\frac{p_y}{p_x}$$

$$\frac{Ed^3N}{dp^3} = \frac{d^3N}{p_T dp_T dy d\phi} = \frac{d^3N}{2\pi\, p_T dp_T dy}\left[1 + \sum_n 2v_n \cos n(\phi - \Phi_R)\right]$$

•Perform a Fourier decomposition of the momentum space particle distributions in the x-y plane

✓ v_2 is the 2nd harmonic Fourier coefficient

v_1=<cosϕ>

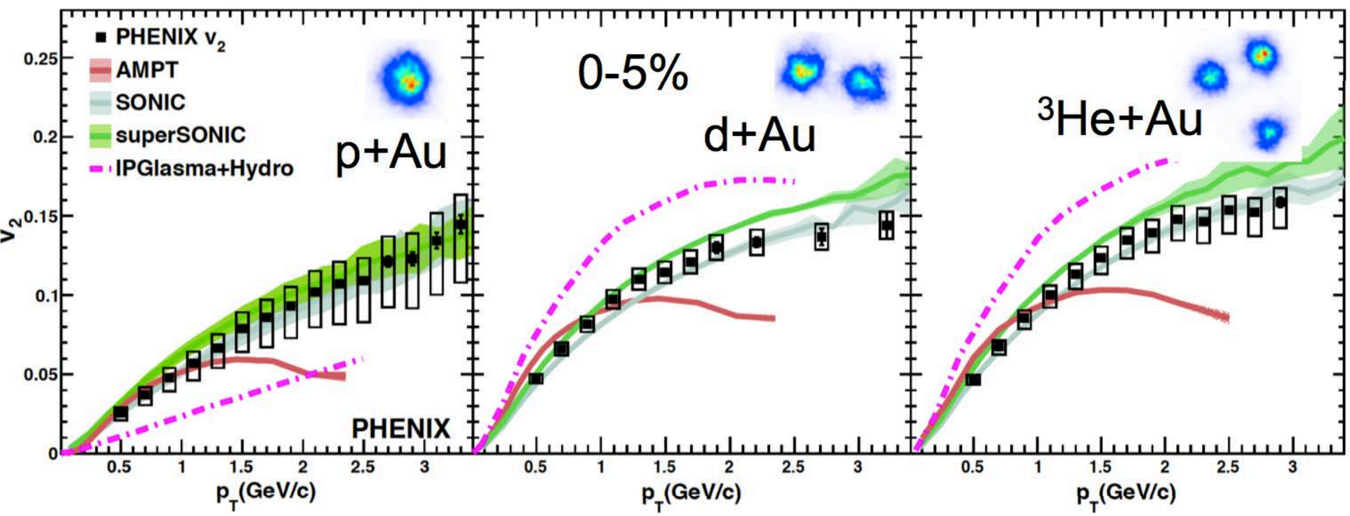
Directed flow zero at midrapidity

v_2=<cos2ϕ>

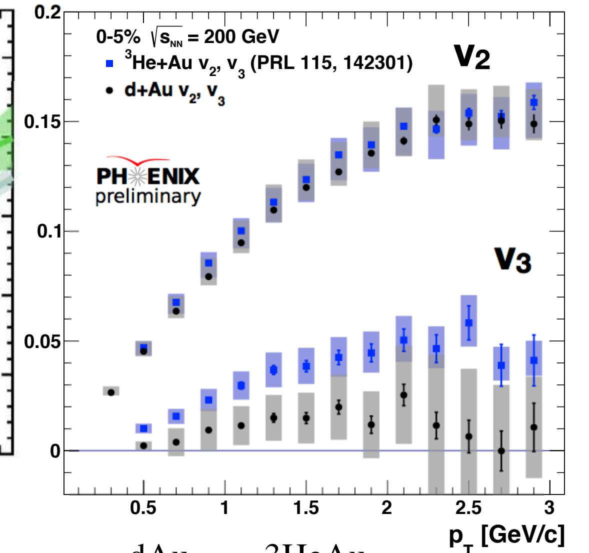
Elliptical flow dominant at midrapidity

Flow is sensitive to the initial geometry

PRC 95 (2017) 034910 PRL 114, 192301, (2015) PRL 115, 142301, (2015)



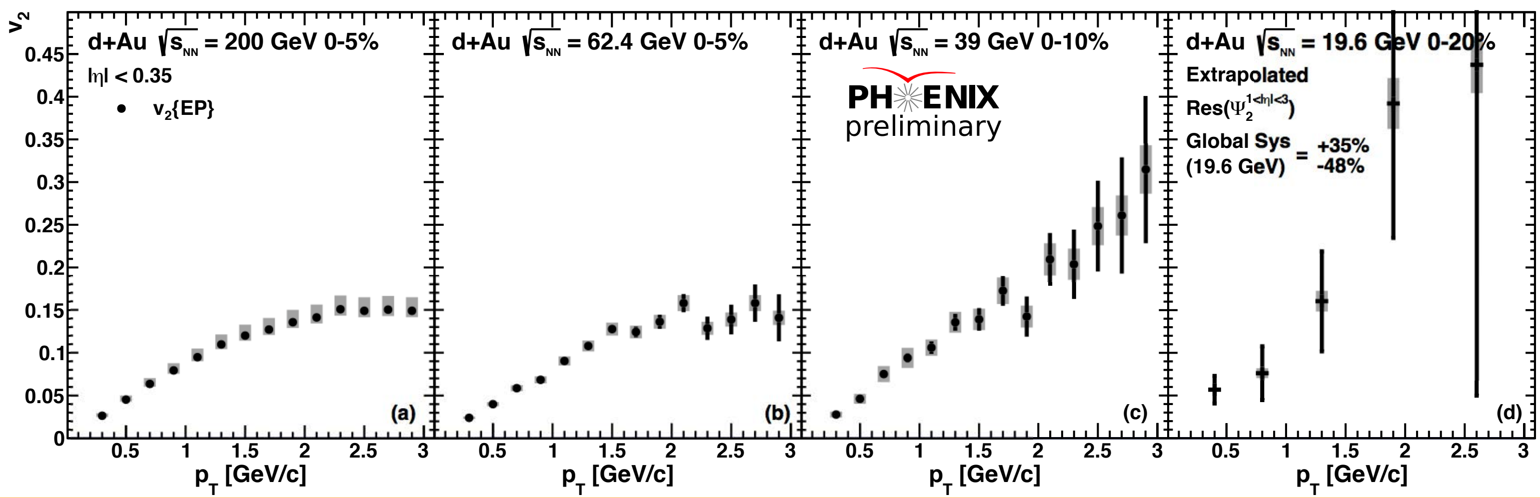
0-5% $\sqrt{s_{NN}}$ = 200 GeV



large non-flow systematic error

$v_2^{pp} < v_2^{dAu} \approx v_2^{3HeAu}$

$v_3^{dAu} < v_3^{3HeAu}$

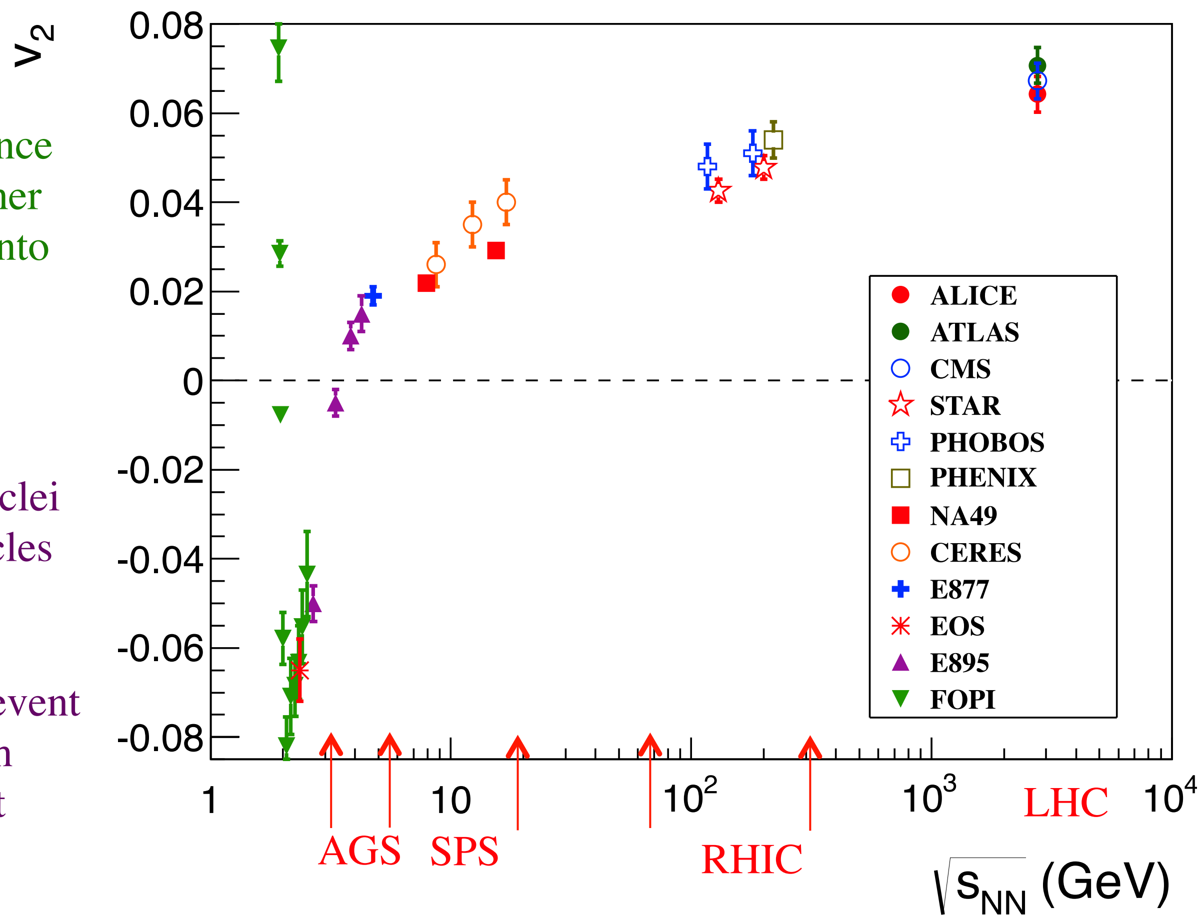


v_2^{dAu} central vs $\sqrt{s}$
Non-flow effects increase with decreasing $\sqrt{s}$

My opinion: small system flow indicates the importance of constituent quarks in initial geometry but likely is not an indication of QGP
Flow exists in all A+A collisions

Nuclei bounce off each other and break into fragments

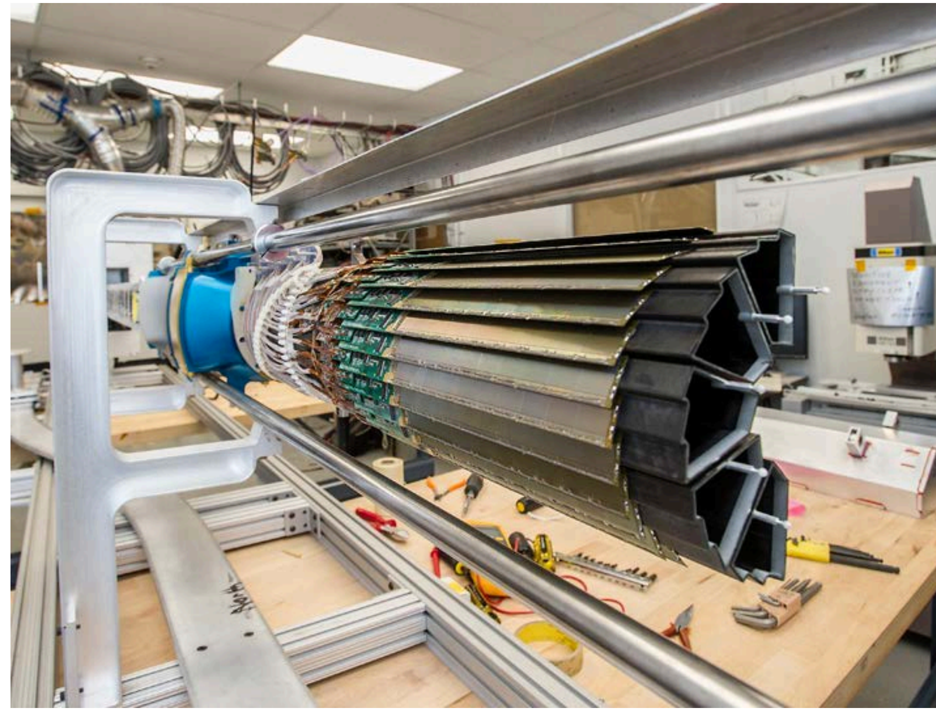
Here slow moving Nuclei make particles but block particles emitted in event plane which squeeze out vertically



Heinz, Snellings ARNPS **63** (2013) 123-151

A new detector STAR Heavy Flavor Tracker

Berkeley Lab's Heavy Flavor Tracker team included (from left) + ENLARGE



A close-up view of components of the Heavy Flavor Tracker, + ENLARGE

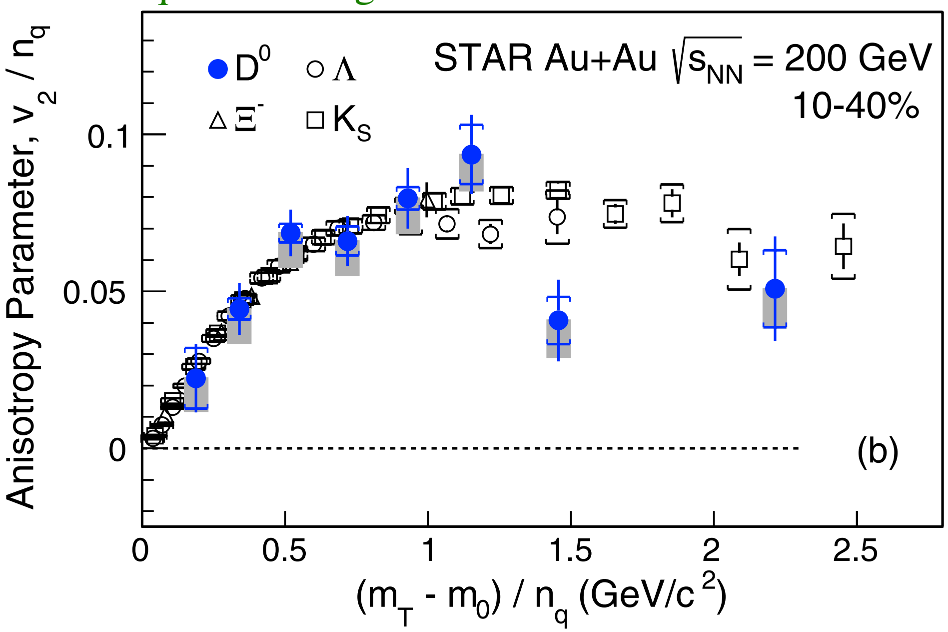
STAR's HFT, a state-of-the-art tracking device, developed by nuclear physicists at Lawrence Berkeley National Laboratory:the HFT is the first silicon detector at a collider that uses Monolithic Active Pixel Sensor technology—the same technology used in digital cameras. The ultrathin sensors—unlike many of the particle detection components of STAR—sit very close to the central beampipe

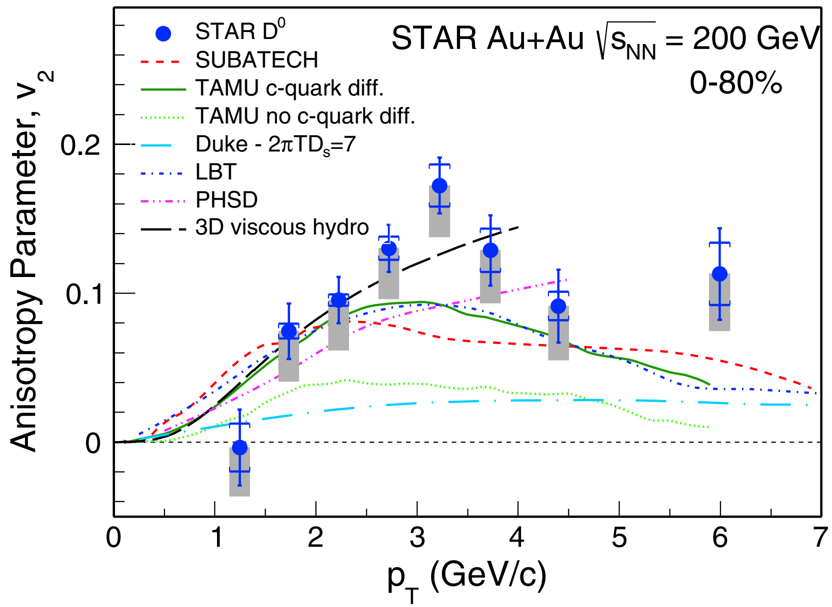
A new detector and a nice flow measurement of open charm (D^0) in Au+Au collisions, but

Constituent quark scaling

STAR PRL **118** (2017) 212301

Comparison to model calculations

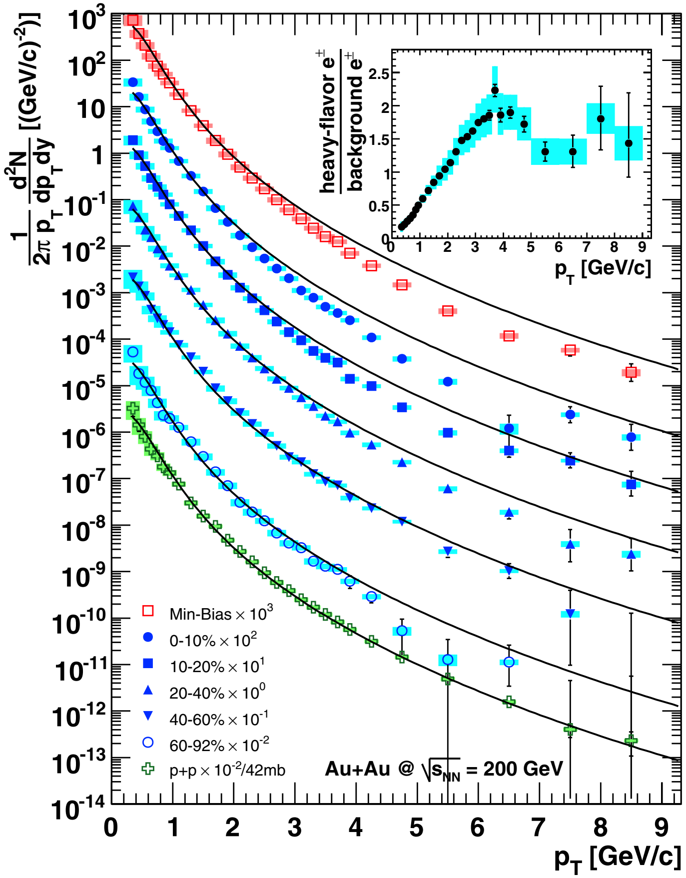


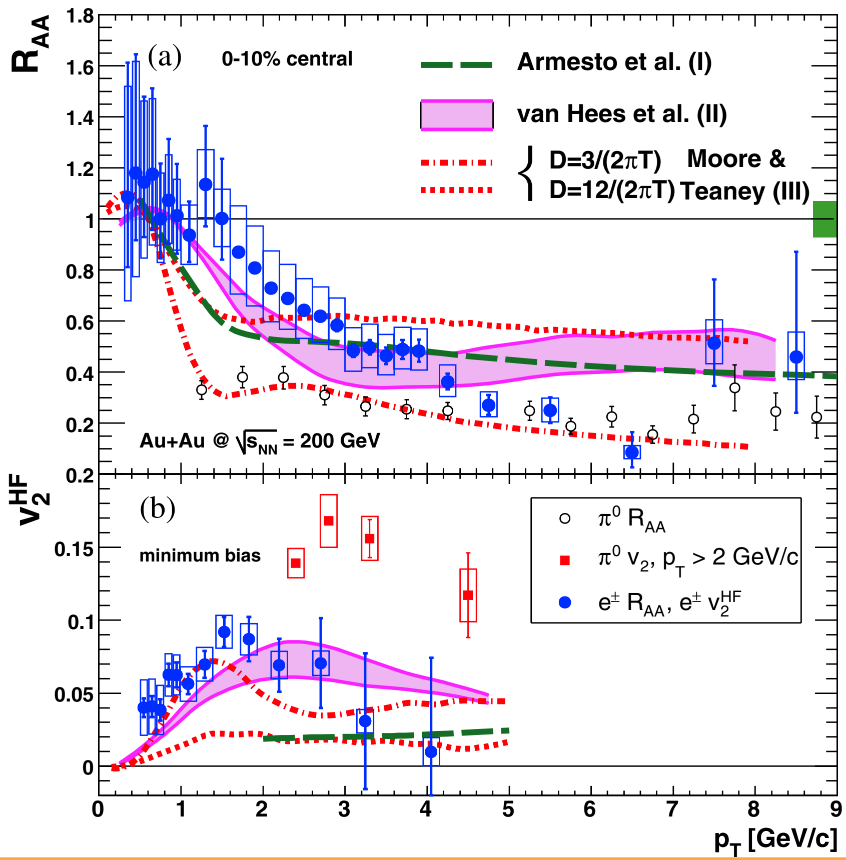


Conclusion: Several theoretical calculations with temperature-dependent, dimensionless charm quark spatial diffusion coefficients (2πTDs) in the range of ~2–12 can simultaneously reproduce our D^0 v_2 result as well as the previously published STAR measurement of the D^0 nuclear modification factor. PRL**113**(2014)142301

Compare with	$2\pi TD_s$	χ^2/NDF
SUBATECH [17]	2–4	15.2/8
TAMU *c* quark diffusion [20]	5–12	10.0/8
TAMU no *c* quark diffusion [20]	...	29.5/8
Duke [19]	7	35.7/8
LBT [21]	3–6	11.1/8
PHSD [16]	5–12	8.7/7
3D viscous hydro [39]	...	3.6/6

but PHENIX did this 10 years ago with prompt single e with numerical results given for η/s



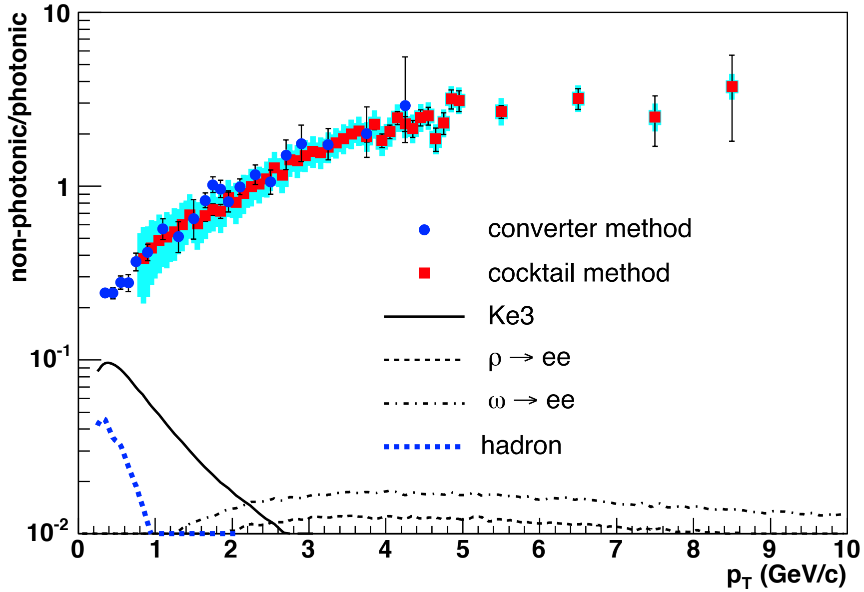


PHENIX PRL 98 (2007) 172301 660 cites

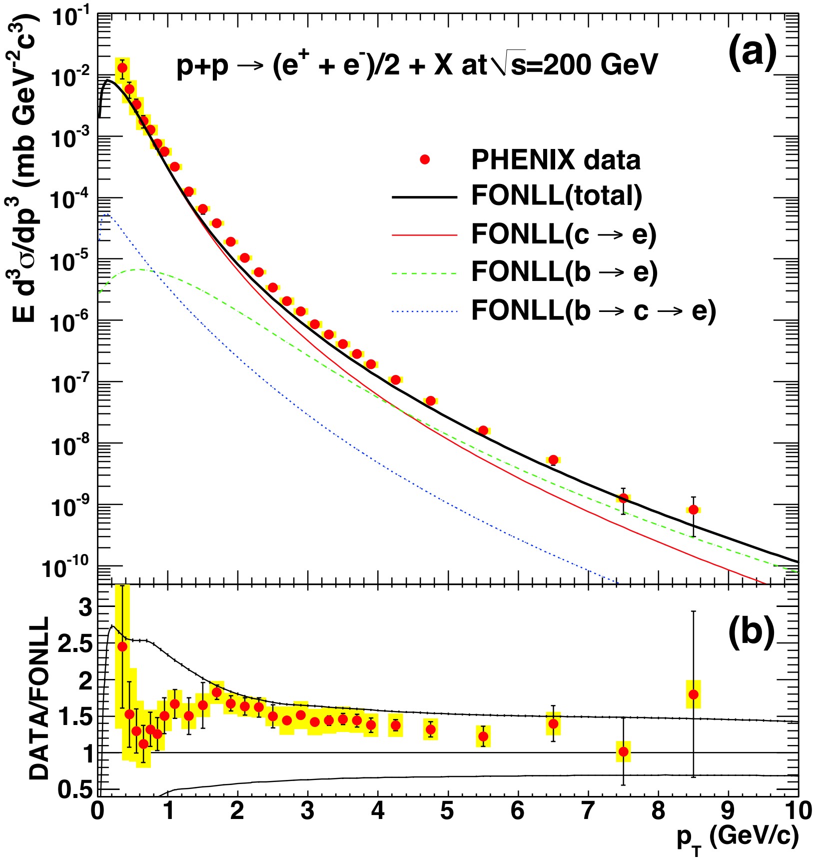
Theory: Moore & Teaney PRC 71 (2005) 064904

A heavy quark thermalizing in the medium is treated as a diffusion problem with diffusion coefficient $D \approx 6\eta/(\varepsilon+p)$. The enthalpy $\varepsilon+p=Ts$ at $\mu_B=0$ which provides an estimate for the viscosity to entropy ratio for $D=(6 \text{ to } 4)/(2\pi T)=6\eta/(Ts)$ of $\eta/s \approx (2 \text{ to } 4/3)/4\pi$, intriguingly close to the conjectured quantum lower bound $\eta/s \approx 1/4\pi$, hence the perfect fluid.

For reference first PHENIX p+p measurement of direct e with details



signal/background vs p_T



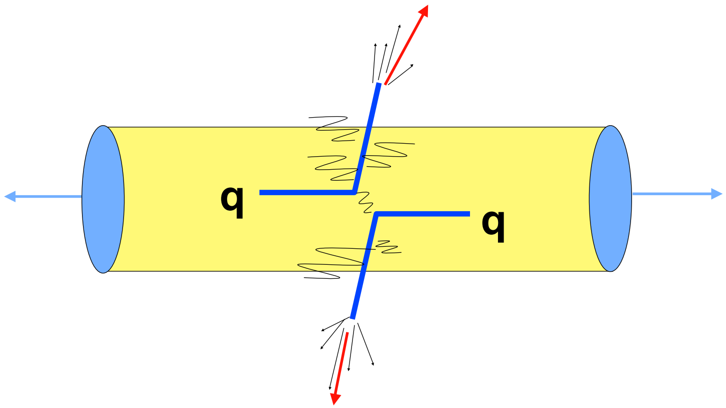
Measurement compared to theory

PHENIX PRL **97** (2006) 252002 292 cites

Jet Quenching: a parton-medium effect
First QCD-based prediction BDMPSZ c. 1997

See Baier, Schiff, Zakharov, Ann. Rev. Nucl. Part. Sci. **50**, 37 (2000).

- Energy loss of an outgoing parton with color charge fully exposed in a medium with a large density of similarly exposed color charges (i.e. a QGP) from LPM coherent radiation of gluons is predicted in QCD by BDMPSZ.



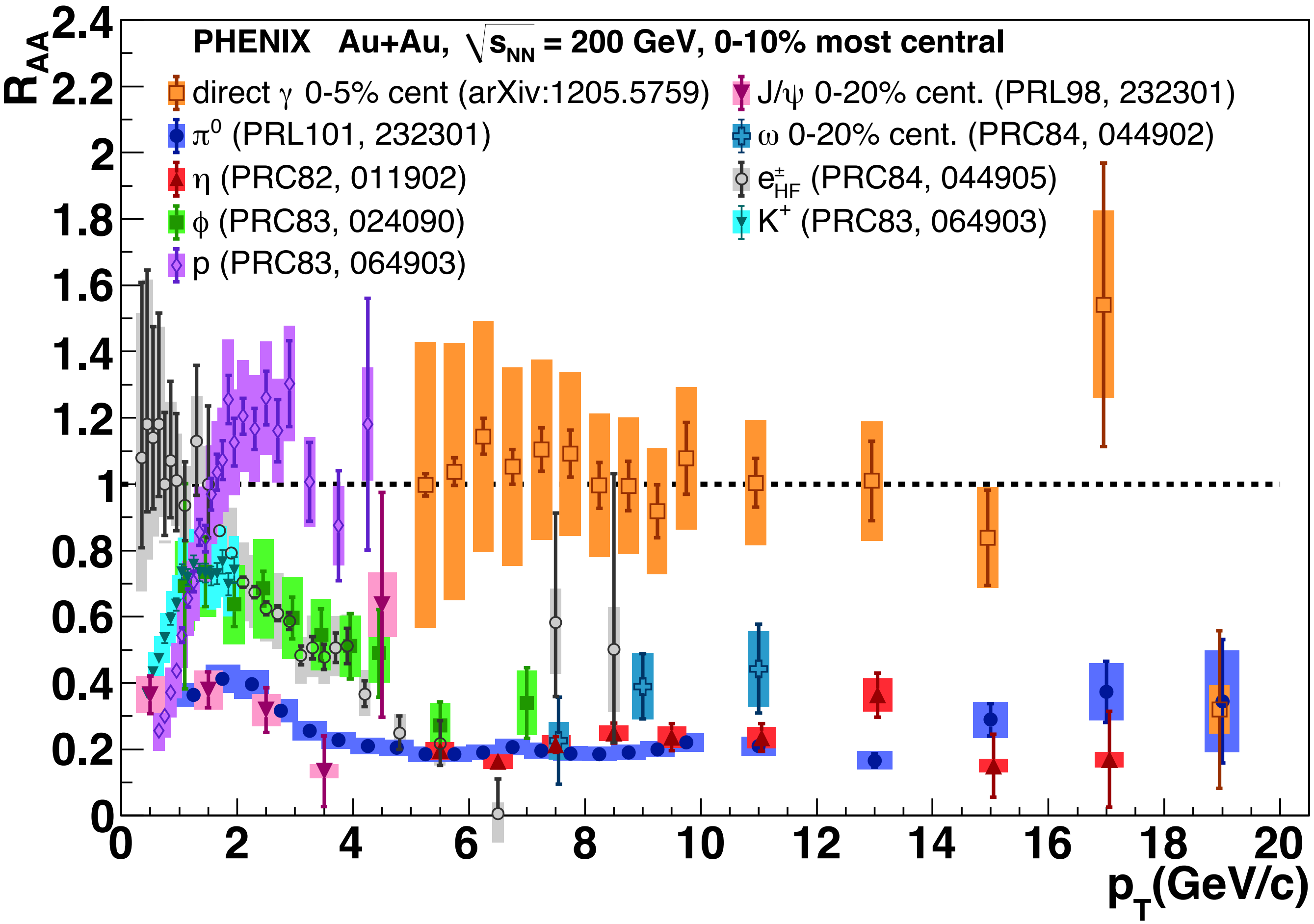
Hard scattered partons lose energy going through the medium so that there are fewer partons or jet fragments at a given p_T The ratio of measured AA to scaled pp cross section which=1for no energy loss is:

$$R_{AA}(p_T) = \frac{d^2N^{\pi}_{AA}/dp_T dy N^{inel}_{AA}}{\langle T_{AA}\rangle d^2\sigma^{\pi}_{pp}/dp_T dy}$$

Lots of evidence for jet Quenching, discovered at RHIC for π^0 and $h^\pm$

PHENIX PRL 88, 022301 (2002) 963 cites

Status of R_{AA} in AuAu at $\sqrt{s_{NN}}$=200 GeV 2013



particle ID is crucial: different particles behave differently

Notable are that ALL particles are suppressed for p_T>2 GeV/c (except for direct-γ), even electrons from c and b quark decay; with one notable exception: the protons are enhanced-(baryon anomaly)

But the BDMPSZ model has 2 predictions

(1) The energy loss of the outgoing parton, $-dE/dx$, per unit length (x) of a medium with total length L, is proportional to the total 4-momentum transfer-squared, $q^2(L)$, and takes the form:

$$\frac{-dE}{dx} \simeq \alpha_s \langle q^2(L) \rangle = \alpha_s \, \mu^2 \, L/\lambda_{\rm mfp} = \alpha_s \, \hat{q} \, L$$

where μ, is the mean momentum transfer per collision, and the transport coefficient $\hat{q} = \mu^2/\lambda_{\rm mfp}$ is the 4-momentum-transfer-squared to the medium per mean free path, $\lambda_{\rm mfp}$.

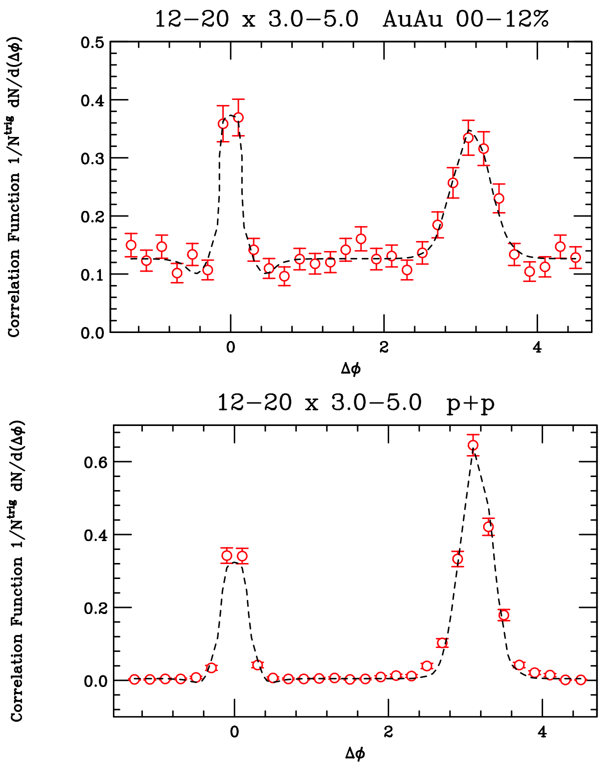
(2) Additionally, the accumulated momentum-squared, $\langle p^2_{\perp W} \rangle$ transverse to a parton traversing a length L in the medium is well approximated by

$$\langle p^2_{\perp W} \rangle \approx \langle q^2(L) \rangle = \hat{q} \, L \qquad \boxed{\langle \hat{q} L \rangle /2 = \left\langle k_T^2 \right\rangle_{AA} - \left\langle k'^2_T \right\rangle_{pp}}$$

since only the component of $\langle p^2_{\perp W} \rangle \perp$ to the scattering plane affects k_T.

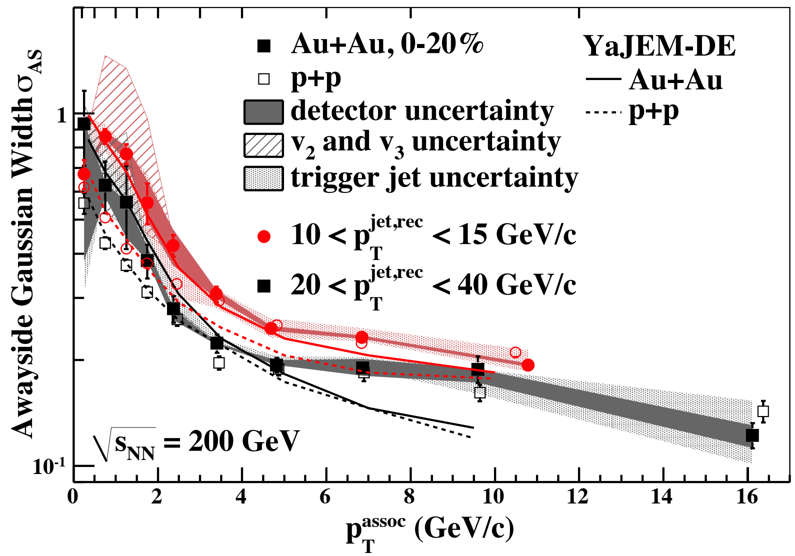
From R_{AA} observed at RHIC (after 12 years) the JET Collab. PRC **90** (2014) 014909 has found that $\hat{q}$ = 1.2±0.3 GeV^2/fm at RHIC, 1.9± 0.7 at LHC at initial time τ_0=0.6 fm/c but nobody has yet measured the azimuthal broadening predicted in (2) !

Results with no broadening or large errors

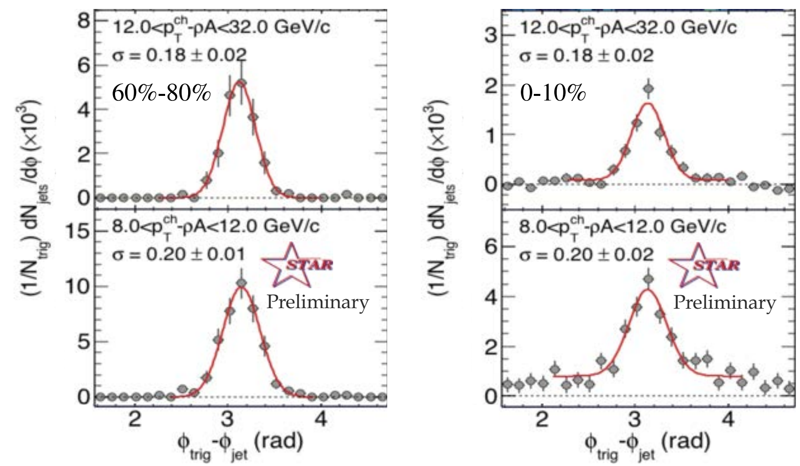


STAR PLB760(2016) 689
p_{Tt}=12-20 GeV/c, p_{Ta}=3-5 GeV/c
AuAu central, $\sqrt{\langle k_T^2\rangle}$=1.42±0.22
p+p $\sqrt{\langle k_T^2\rangle}$=2.51±0.31 GeV/c

MJT-$\langle \hat{q}L\rangle$ with this data 1702.00840v2

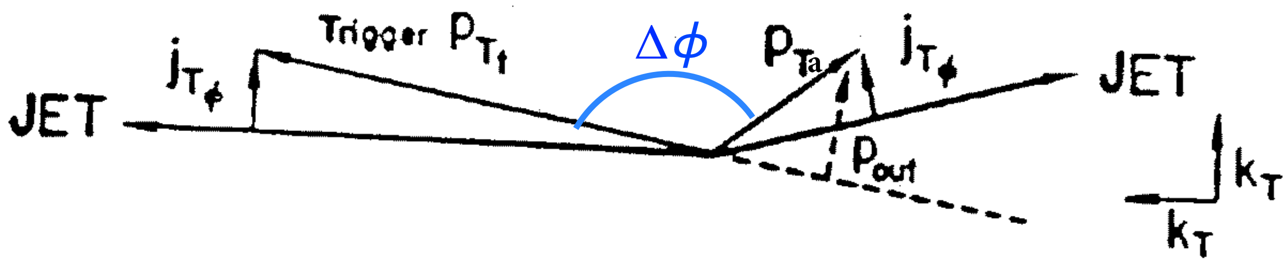


STAR Jet-hadron
PRL112(2014)122301



STAR Jet-Jet NPA956(2016)641

Understanding k_T and the new k'_T



Thanks to FFF, k_T is the transverse momentum of **a quark** in **a nucleon** so for a p+p or n+n collision the two k_T add vectorially at random. It is easier to understand from the figure above where the two k_T are represented as: vertical, which gives the azimuthal decorrelation of the two jets; and horizontal which changes the p_{Tt} of the trigger jet

We calculate $\langle k_T^2 \rangle$ from p+p and Au+Au di-hadron measurements with the same trigger particle transverse momentum, p_{Tt}, away-side p_{Ta}, $x_h = p_{Ta}/p_{Tt}$ and $p_{\rm out} \equiv p_{Ta} \sin\Delta\phi$. The di-hadrons are assumed to be fragments of jets with transverse momenta $\hat{p}_{Tt}$ and $\hat{p}_{Ta}$ with ratio $\hat{x}_h = \hat{p}_{Ta}/\hat{p}_{Tt}$, where $z_t \simeq p_{Tt}/\hat{p}_{Tt}$ is the fragmentation variable, the fraction of momentum of the trigger particle in the trigger jet, and j_T is the jet fragmentation transverse momentum.

$$\sqrt{\langle k_T^2 \rangle} = \frac{\hat{x}_h}{\langle z_t \rangle} \sqrt{\frac{\langle p_{\rm out}^2 \rangle - (1 + x_h^2) \langle j_T^2 \rangle /2}{x_h^2}}$$

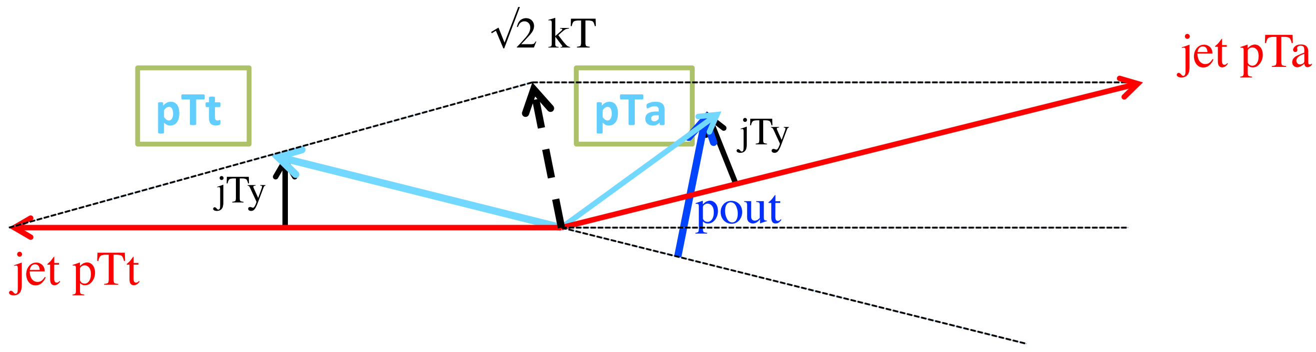
The key new idea (k'_T) gives an elegant Solution

For a di-jet produced in a hard scattering, the initial $\hat{p}_{Tt}$ and $\hat{p}_{Ta}$ will both be reduced by energy loss in the medium to become $\hat{p}'_{Tt}$ and $\hat{p}'_{Ta}$ which will be measured by the di-hadron correlations with p_{Tt} and p_{Ta} in Au+Au collisions. As both jets from the initial di-jet lose energy in the medium, the azimuthal angle between the di-jets from the $\langle k_T^2 \rangle$ in the original collision should not change unless the medium induces multiple scattering from $\hat{q}$. Thus, without $\hat{q}$ and assuming the same fragmentation transverse momentum $\langle j_T^2 \rangle$ in the original jets and those that have lost energy, the $p_{\rm out}$ between the away hadron with p_{Ta} and the trigger hadron with p_{Tt} will not change, but the $\left\langle k'^2_T \right\rangle$ will be reduced because the ratio of the away to the trigger jets $\hat{x}'_h = \hat{p}'_{Ta}/\hat{p}'_{Tt}$ will be reduced. Thus the calculation of k'_T from the di-hadron p+p measurement to compare with Au+Au measurement with the same di-hadron trigger p_{Tt} and p_{Ta} must use the values of $\hat{x}_h$, and $\langle z_T \rangle$ from the Au+Au measurement to compensate for the energy lost by the original dijet in p+p collisions.

The same values of $\hat{x}_h$, and $\langle z_T \rangle$ in Au+Au and p+p gives the cool result:

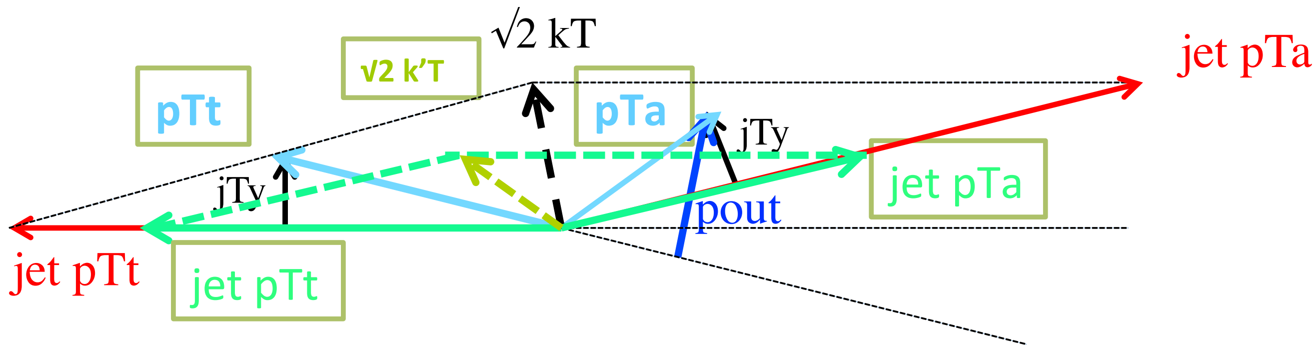
$$\boxed{\langle \hat{q} L \rangle /2 = \left[\frac{\hat{x}_h}{\langle z_t \rangle}\right]^2 \left[\frac{\left\langle p_{\rm out}^2 \right\rangle_{AA} - \left\langle p_{\rm out}^2 \right\rangle_{pp}}{x_h^2}\right]}$$

The solution in pictures



Initial configuration a di-jet with k_T and fragments with p_{out} .

The solution in pictures



Final configuration a di-jet with k'_T and fragments with p_{out} .

Find q-hat from the STAR data

- A) Bjorken parent-child relation and `trigger-bias' proves that the power **n** of the jet p_T distribution is the same as the power of the π^0's
- B) Calculate $\langle z_t \rangle$ from the quark or gluon fragmentation fn or both. This is easy for the STAR paper who measured $\langle z_t \rangle = 0.80 \pm 0.05$ in their p+p collisions for π^0 with $12 < p_{Tt} < 20$ GeV/c
- C) Fit the away-side peak in the correlation fn. to a gaussian in p_{out}
- D) \hat{x}_h the ratio of the away-jet to the trigger jet transverse momenta can be measured by the away particle p_{Ta} distribution for a given trigger particle p_{Tt}. STAR calls this z_T and I call it x_E from the CERN ISR where it was discovered 40 years ago.

Table 1: Tabulations for $\hat{q}$–STAR π^0-h MJT PLB(2017)

STAR PLB760(2016)689–696

$\sqrt{s_{NN}} = 200$GeV	$\langle p_{Tt} \rangle$	$\langle p_{Ta} \rangle$	$\sqrt{\langle k_T^2 \rangle_{AA}}$	$\sqrt{\langle k'^2_T \rangle_{pp}}$	$\langle \hat{q} L \rangle$	$\hat{q}$ ($\langle L \rangle$=7fm)
Reaction	GeV/c	GeV/c	GeV/c	GeV/c	GeV^2	GeV^2/fm
Au+Au 0-12%	14.71	1.72	2.28 ± 0.35	1.006 ± 0.18	8.41 ± 2.66	1.20 ± 0.38
Au+Au 0-12%	14.71	3.75	1.42 ± 0.22	1.076 ± 0.18	1.71 ± 0.67	0.24 ± 0.10

A)PHENIXπ^0 p+p Au+Au PRL101(2008)232301

Power Law p_T>3GeV/c all centralities n=8.10±0.05

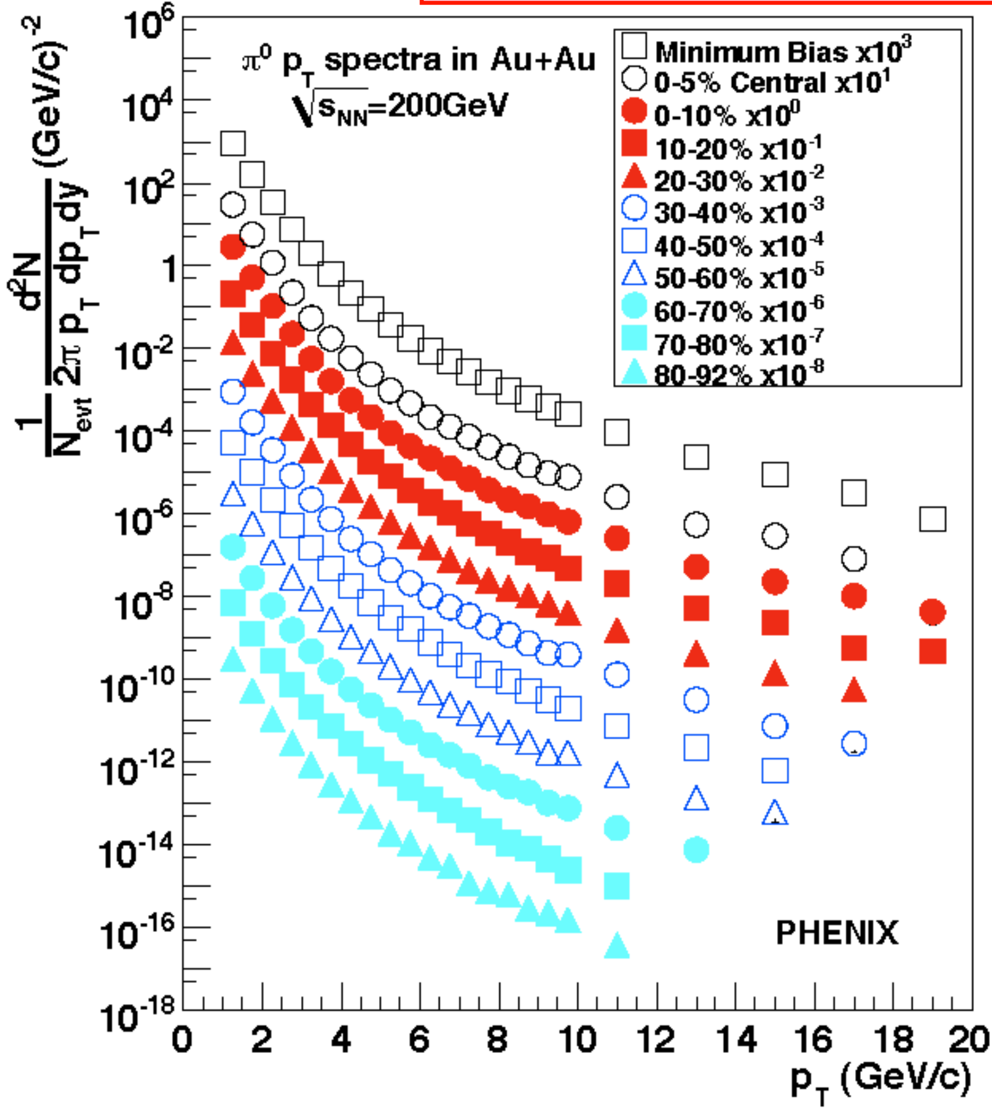


Table 5: Fit parameters for p_T>3 GeV/c

System	A	n	χ^2/NDF
p+p	14.61±1.45	8.12±0.05	5.68/17
Au+Au 0-5 %	81.18±10.30	8.20±0.07	9.66/16
Au+Au 0-10 %	75.28±8.89	8.18±0.06	10.62/17
Au+Au 10-20 %	64.62±7.64	8.19±0.06	10.04/17
Au+Au 20-30 %	49.33±5.78	8.18±0.06	6.63/16
Au+Au 30-40 %	30.85±3.53	8.10±0.06	10.63/16
Au+Au 40-50 %	22.58±2.61	8.13±0.06	3.50/15
Au+Au 50-60 %	12.40±1.48	8.06±0.07	8.09/15
Au+Au 60-70 %	6.25±0.78	8.03±0.07	2.89/14
Au+Au 70-80 %	3.38±0.45	8.12±0.08	8.42/13
Au+Au 80-92 %	1.19±0.18	8.03±0.09	9.84/13
Au+Au 0-92 %	29.31±3.07	8.17±0.05	6.83/17

The leading-particle effect a.k.a. trigger bias

- Due to the steeply falling power-law spectrum of the scattered partons, the inclusive particle p_T spectrum is dominated by fragments biased towards large z. This was unfortunately called trigger bias by M. Jacob and P. Landshoff, Phys. Rep. **48C**, 286 (1978) although it has nothing to do with a trigger.

$$\frac{d^2\sigma_\pi(\hat{p}_{T_t}, z_t)}{d\hat{p}_{T_t} dz_t} = \frac{d\sigma_q}{d\hat{p}_{T_t}} \times D^q_\pi(z_t)$$

Fragment spectrum given $\hat{p}_{T_t}$

$$= \frac{A}{\hat{p}_{T_t}^{n-1}} \times D^q_\pi(z_t)$$

Let $\hat{p}_{T_t} = p_{T_t}/z_t \qquad d\hat{p}_{T_t}/dp_{T_t}|_{z_t} = 1/z_t$

$$\frac{d^2\sigma_\pi(p_{T_t}, z_t)}{dp_{T_t} dz_t} = \frac{A}{p_{T_t}^{n-1}} \times z_t^{n-2} D^q_\pi(z_t)$$

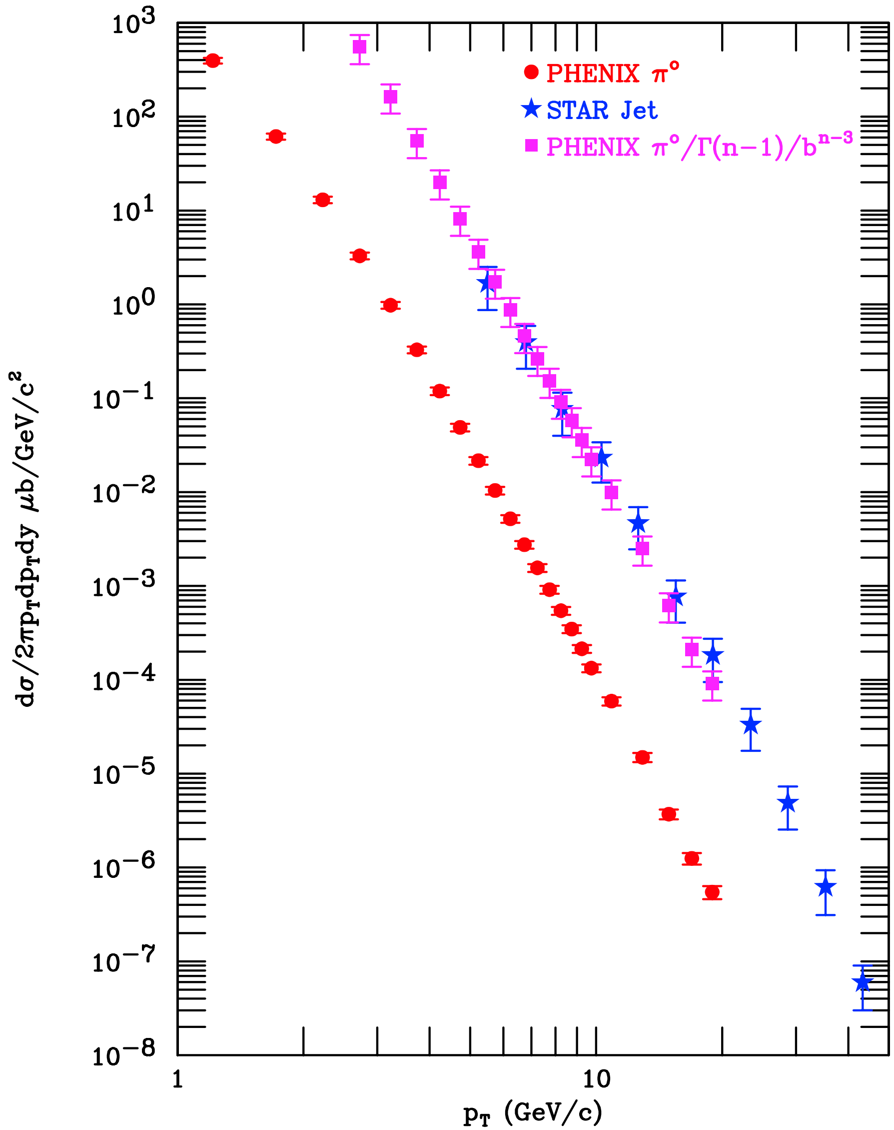
Fragment spectrum given p_{Tt} is weighted to high z_t by z_t^{n-2}

$$D^q_\pi(z_t) = Be^{-bz_t}$$

$$\boxed{\frac{1}{p_{T_t}} \frac{d\sigma_\pi}{dp_{T_t}} \approx \frac{\Gamma(n-1)}{b^{n-1}} \frac{AB}{p_{T_t}^n}}$$

Bjorken parent-child relation: parton and particle invariant p_T spectra have same power n, etc.

It works: Jet p_T spectrum same power n as π^0



$$\frac{1}{p_{T_t}} \frac{d\sigma_\pi}{dp_{T_t}} \approx \frac{\Gamma(n-1)}{b^{n-1}} \frac{AB}{p_{T_t}^n}$$

C) Fits to the correlation functions for <pout^2>

- Fit the correlation function with a trigger side gaussian in $\Delta\Phi$ and an away side gaussian in $\sin(\Delta\Phi-\pi=x)$, where $-\pi/2<x<\pi/2$, which can easily be converted to $\sqrt{\langle p^2_{out}\rangle}$ by multiplying the fit result by p_{Ta}.

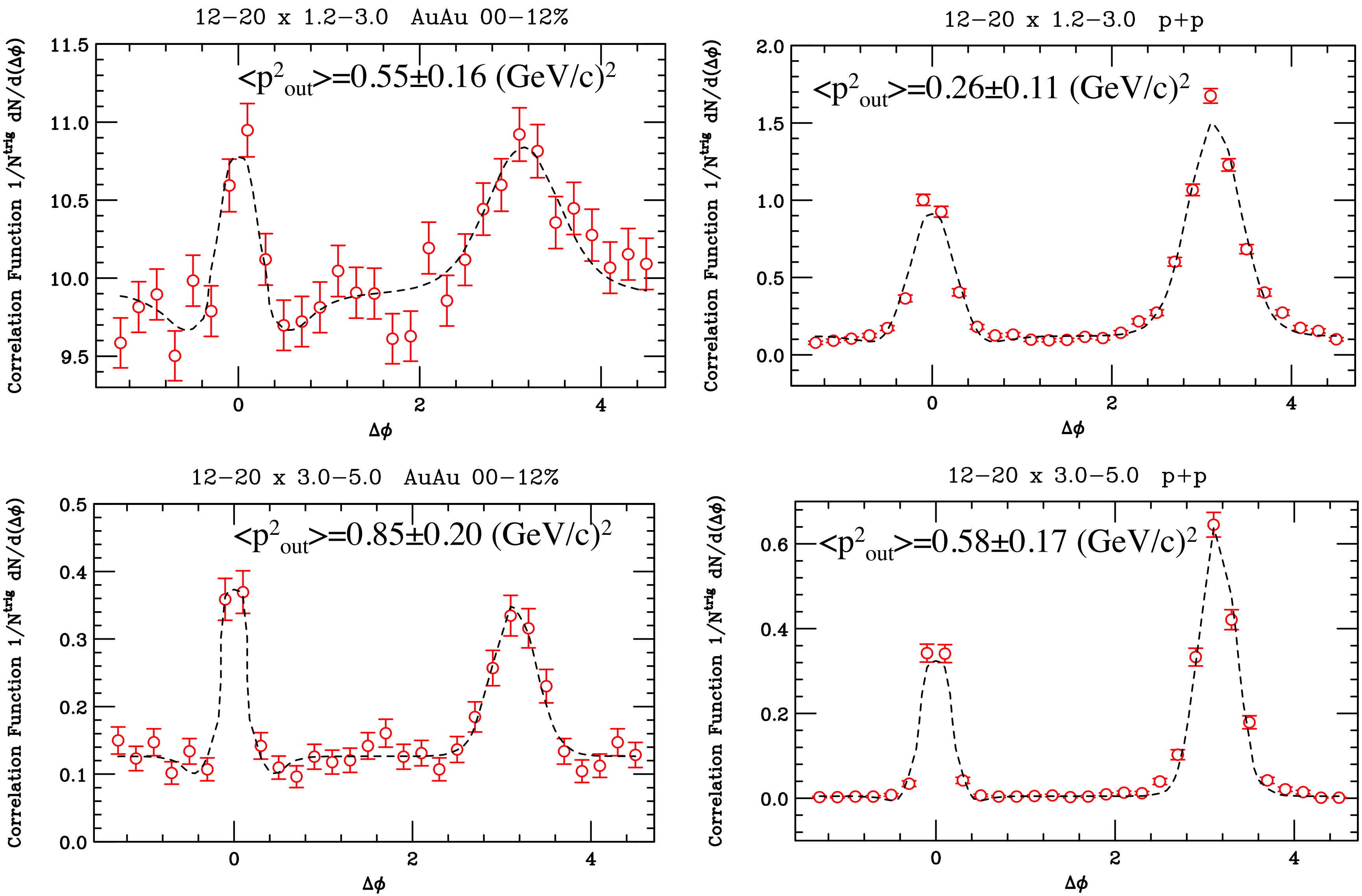
For the away-side, $-\pi/2 < \Delta\phi < 3\pi/2$, let $x = \Delta\phi - \pi$. I defined a variable $\sigma_{nop} = \sigma_y/p_{Ta} = \sqrt{\langle \sin^2 x\rangle}$ and fit for that instead of just fitting for $\sqrt{\langle x^2\rangle}$. Then after the fit, multiply $\sigma_{nop} \times p_{Ta} = \sigma_y = \sqrt{\langle p^2_{\rm out}\rangle}$.

$$\frac{df(x)}{dx} = \frac{N_a}{\mathrm{erf}(1.0/(\sigma_{nop}\sqrt{2}))} \times \frac{\cos x}{\sigma_{nop}\sqrt{2\pi}} \exp\frac{-(\sin x)^2}{2\sigma^2_{nop}} \quad . \tag{14}$$

Then set:

$$\sqrt{\langle p^2_{\rm out}\rangle} = p_{Ta} \times \sigma_{nop} \tag{15}$$

C) p_{out} fits are good



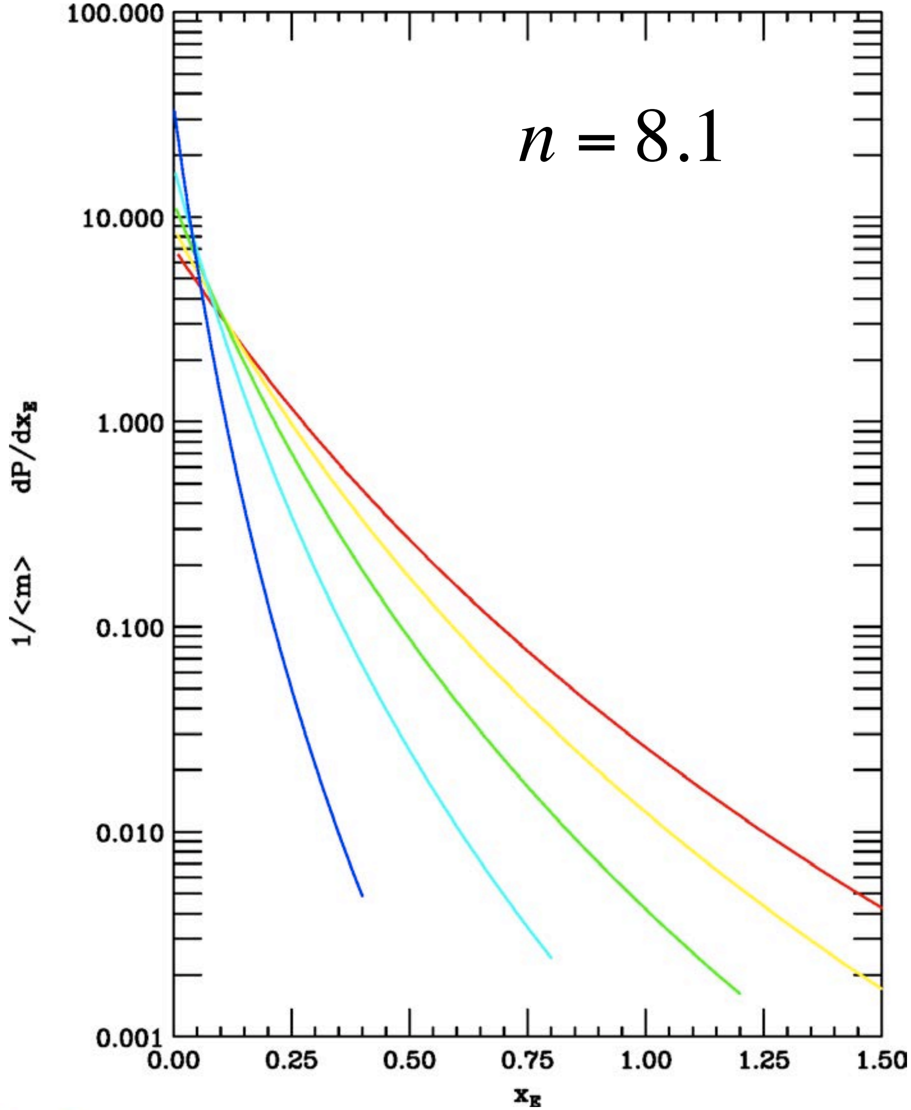
D) The away particle p_{Ta} distribution for a given trigger particle p_{Tt} measures the ratio of the away jet to trigger jet p_T $x_E \approx p_{Ta}/p_{Tt}$ (STAR calls z_T)

4.2 The ratio of the away jet to the trigger jet, $\hat{x}_h = \hat{p}_{Ta}/\hat{p}_{Tt}$.

$$\left.\frac{dP_\pi}{dx_E}\right|_{p_{T_t}} = N\,(n-1)\frac{1}{\hat{x}_h}\frac{1}{(1+\frac{x_E}{\hat{x}_h})^n}$$

Full derivation in Appendix or see PHENIX π^0 p+p PRD74(2006)072002

D) Shape of x_E distribution depends on $\hat{x}_h$ and *n* but not on *b*-i.e. FFF failed



$$\left.\frac{dP_\pi}{dx_E}\right|_{p_{T_t}} \approx N\,(n-1)\frac{1}{\hat{x}_h}\frac{1}{(1+\frac{x_E}{\hat{x}_h})^n}$$

$\hat{x}_h$

1.0

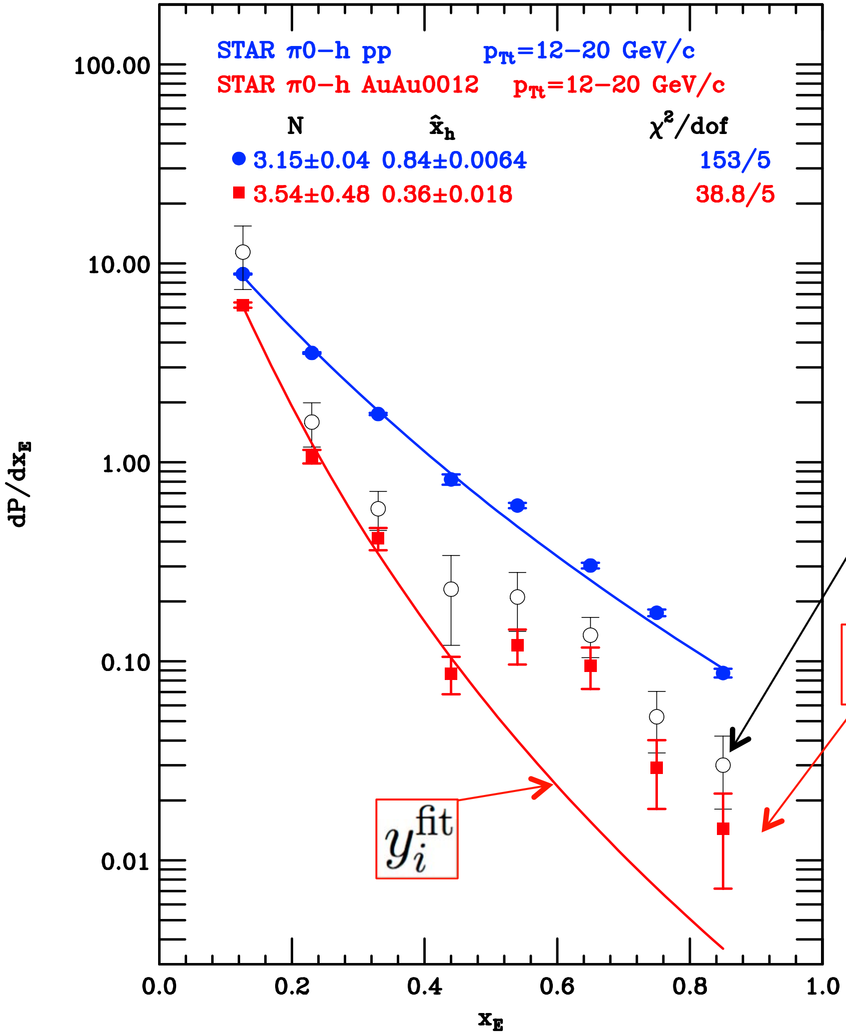
0.8

0.6

0.4

0.2

Here FYI is my fit to the STAR x_E (z_T) distribution with huge Type B sys errors



$$\chi^2 = \left[\sum_{i=1}^{n} \frac{(y_i + \epsilon_b \sigma_{b_i} - y_i^{\rm fit})^2}{\tilde{\sigma}_i^2}\right] + \epsilon_b^2$$

$$\tilde{\sigma}_i = \sigma_i \left(1 + \epsilon_b \sigma_{b_i}/y_i\right)$$

y_i with sys error σ_{bi}

$y_i + \epsilon_b \sigma_{b_i}$ with errors $\tilde{\sigma}_i$ and $\epsilon_b = -1.3 \pm 0.5$.

$$\hat{x}_h = 0.36 \pm 0.05$$

Discussion

The result for the lower ($\langle p_{Ta}\rangle = 1.72$ GeV/c) bin of $\langle \hat{q}L\rangle = 8.41 \pm 2.66$ GeV^2 is 3.2 σ from zero. The result for ($\langle p_{Ta}\rangle = 3.75$ GeV/c) bin, $\langle \hat{q}L\rangle = 1.71 \pm 0.67$ GeV^2, is at the edge of agreement, 2.4 σ below the value in the lower p_{Ta} bin, but also 2.6 σ from zero. If the different p_{Ta} ranges do not change the original di-jet configuration, then the value of $\langle \hat{q}L\rangle$ should be equal in both ranges and can be weighted averaged with a result of $\langle \hat{q}L\rangle = 2.11 \pm 0.64$ GeV^2. Taking a guess for $\langle L\rangle$ in an Au+Au central collision as 7 fm, half the diameter of an Au nucleus, the result would be $\hat{q} = 1.20 \pm 0.38$ GeV^2/fm for the lowest p_{Ta} bin, $\hat{q} = 0.24 \pm 0.096$ GeV^2/fm for the higher p_{Ta} bin, with weighted average $\hat{q} = 0.30 \pm 0.09$ GeV^2/fm. These results are close to or lower than the result of the JET collaboration $\hat{q} = 1.2 \pm 0.3$ GeV^2/fm at $\tau_0 = 0.6$ fm/c. However the di-jet spends $\tau \sim 7 - 14$ fm/c in the medium which may affect the value of $\hat{q}$ to be compared with the JET collaboration result which used only single (trigger) hadrons for their calculation.

$\sqrt{s_{NN}} = 200$GeV	$\langle p_{Tt}\rangle$	$\langle p_{Ta}\rangle$	$\sqrt{\langle k_T^2\rangle}_{AA}$	$\sqrt{\langle k'^2_T\rangle}_{pp}$	$\langle \hat{q}L\rangle$	$\hat{q}$ ($\langle L\rangle$=7fm)
Reaction	GeV/c	GeV/c	GeV/c	GeV/c	GeV^2	GeV^2/fm
Au+Au 0-12%	14.71	1.72	2.28 ± 0.35	1.006 ± 0.18	8.41 ± 2.66	1.20 ± 0.38
Au+Au 0-12%	14.71	3.75	1.42 ± 0.22	1.076 ± 0.18	1.71 ± 0.67	0.24 ± 0.10

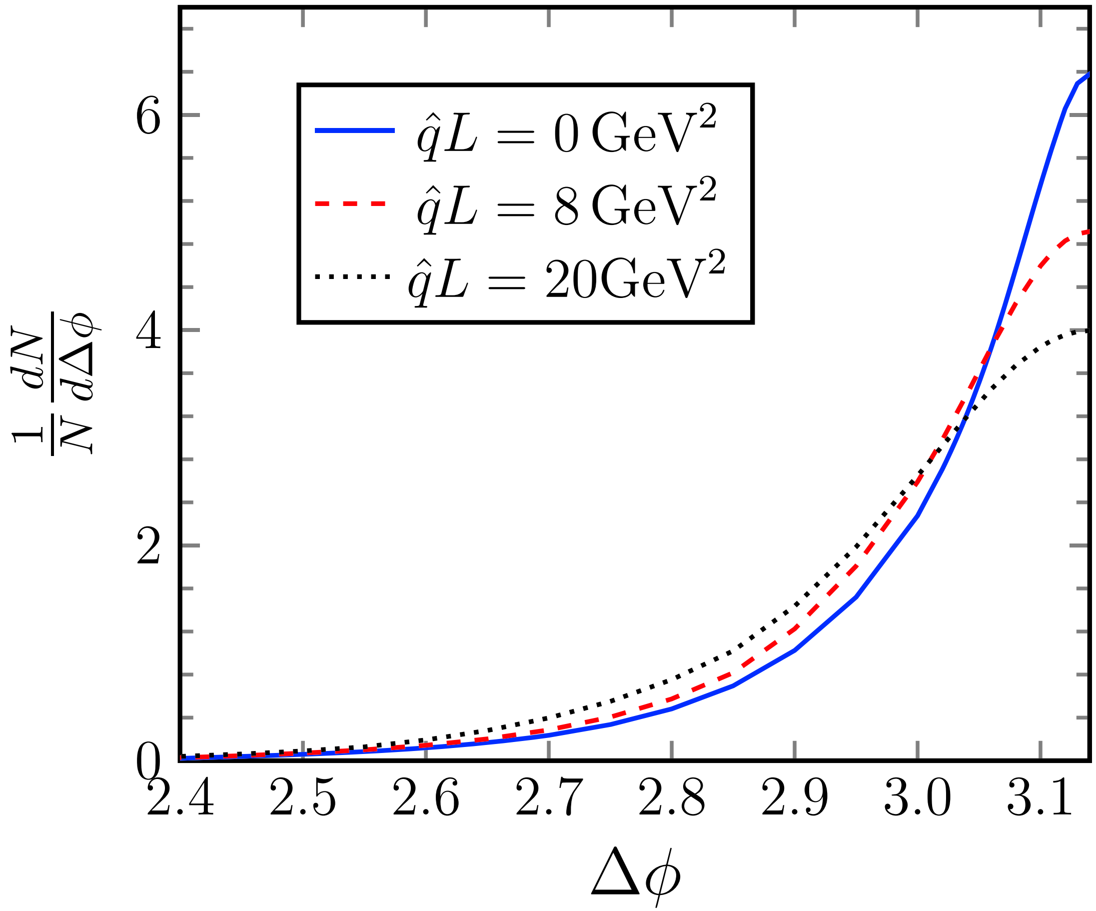
The Challenge

It is important to emphasize that the calculated values of $\langle \hat{q}L \rangle$ are proportional to the square of the value of $\hat{x}_h$ derived from the measured away-side z_T (i.e. x_E) distribution. Although in the literature for more than a decade in a well-cited paper and referenced in an important QCD Resource Letter [Kronfeld,Quigg Am. J. Phys. **78** (2010) 1081], this equation has neither been verified nor falsified by a measurement of di-jet correlations with a di-hadron trigger. Future measurements at RHIC will be able to do this and thus greatly improve the understanding of di-jet and di-hadron azimuthal broadening. See prediction of [A.Mueller, *et al.* Phys. Lett. B**763** (2016) 208] for $p_T = 35$ GeV/c jets at RHIC.

Homework

Dijet Angular Correlation at RHIC

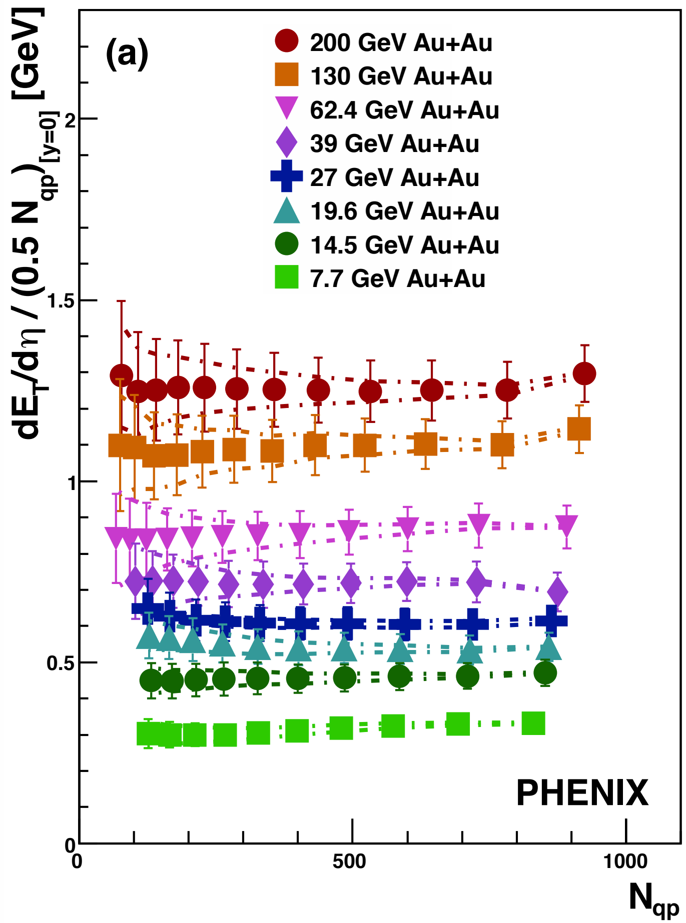
A.Mueller et al PLB **763** (2016) 208

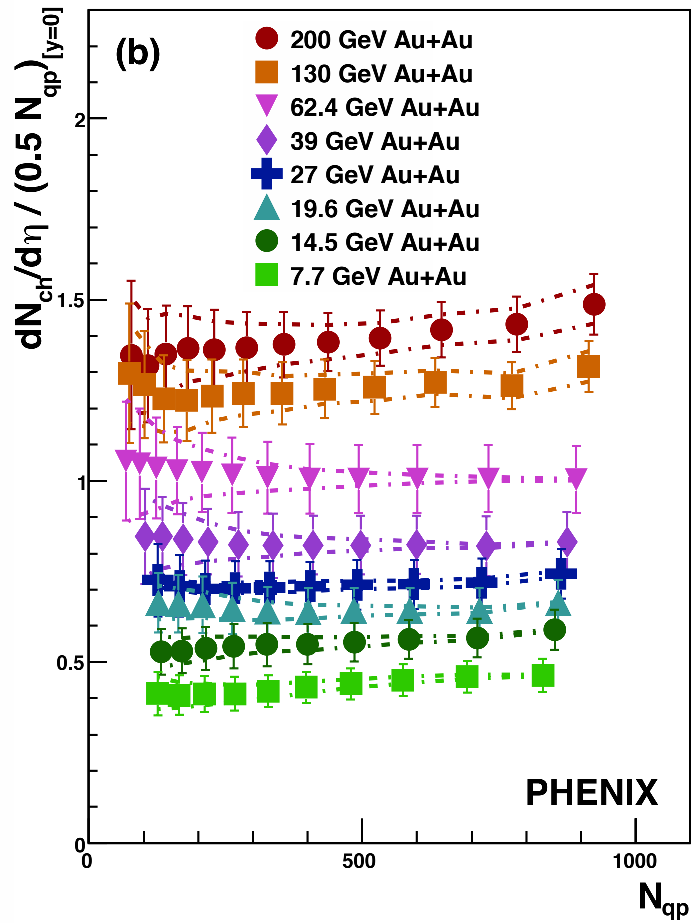


$$\langle \hat{q}L \rangle /2 = \left[\frac{\hat{x}_h}{\langle z_t \rangle}\right]^2 \left[\frac{\langle p_{\mathrm{out}}^2 \rangle_{AA} - \langle p_{\mathrm{out}}^2 \rangle_{pp}}{x_h^2}\right]$$

Does the formula give the same answer for qhatL from $<p^2_{out}>$ of the above predictions at RHIC for 35 GeV Jets?

Constituent-quark-participant scaling-N_{qp}

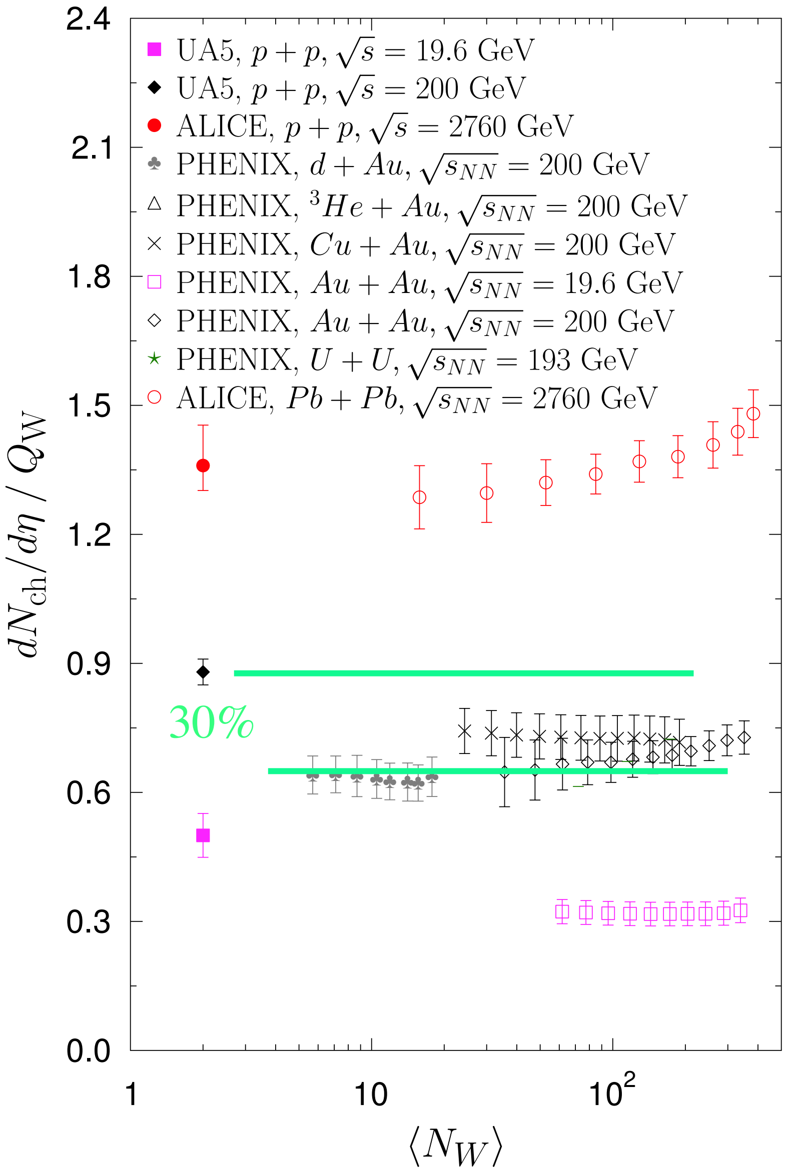




PHENIX PRC93(2016)024901

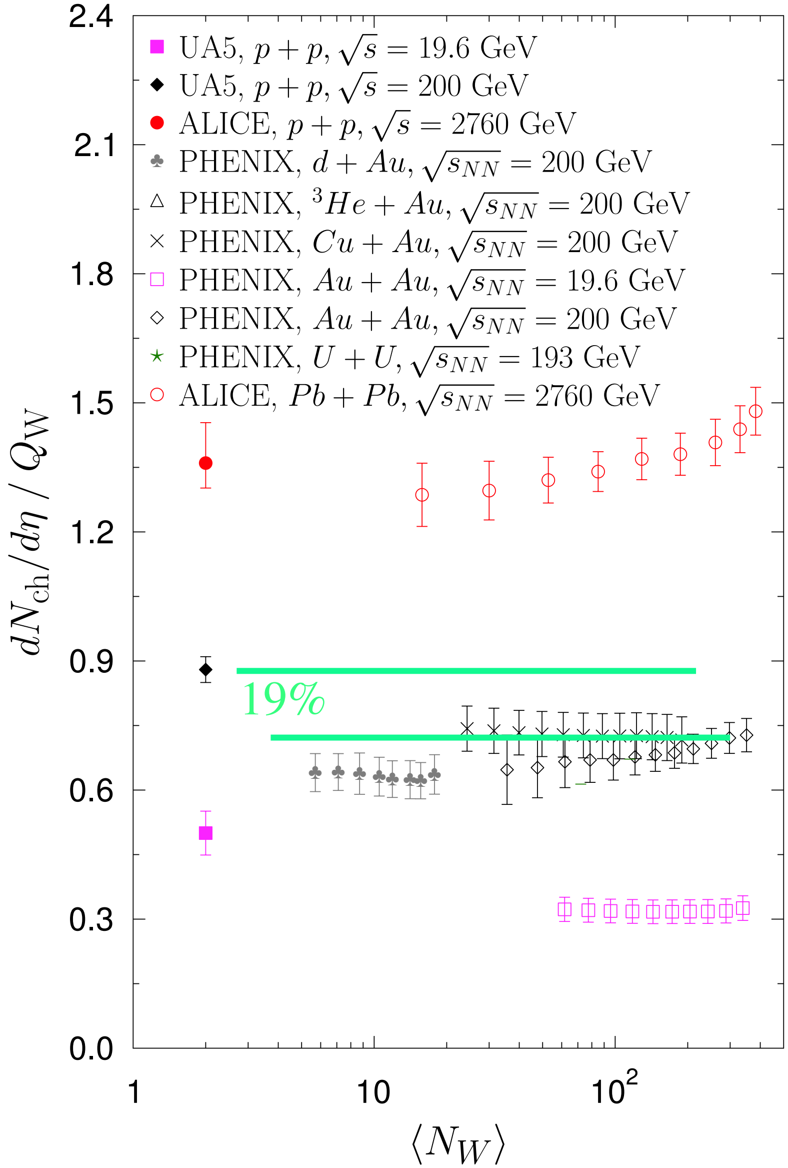
An exercise in systematic errors!

Disagreement from another NQP calculation?



Bozek, Broniowski, Rybczynski PRC94(2016)014902 do a constituent quark participant calculation which they call Q_W (wounded quark) and find that it works for ALICE Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV "but we note in Fig. 1 that at $\sqrt{s_{NN}}$=200 GeV the corresponding p + p point is higher by about 30% from the band of other reactions"(only from the lowest AuAu point)

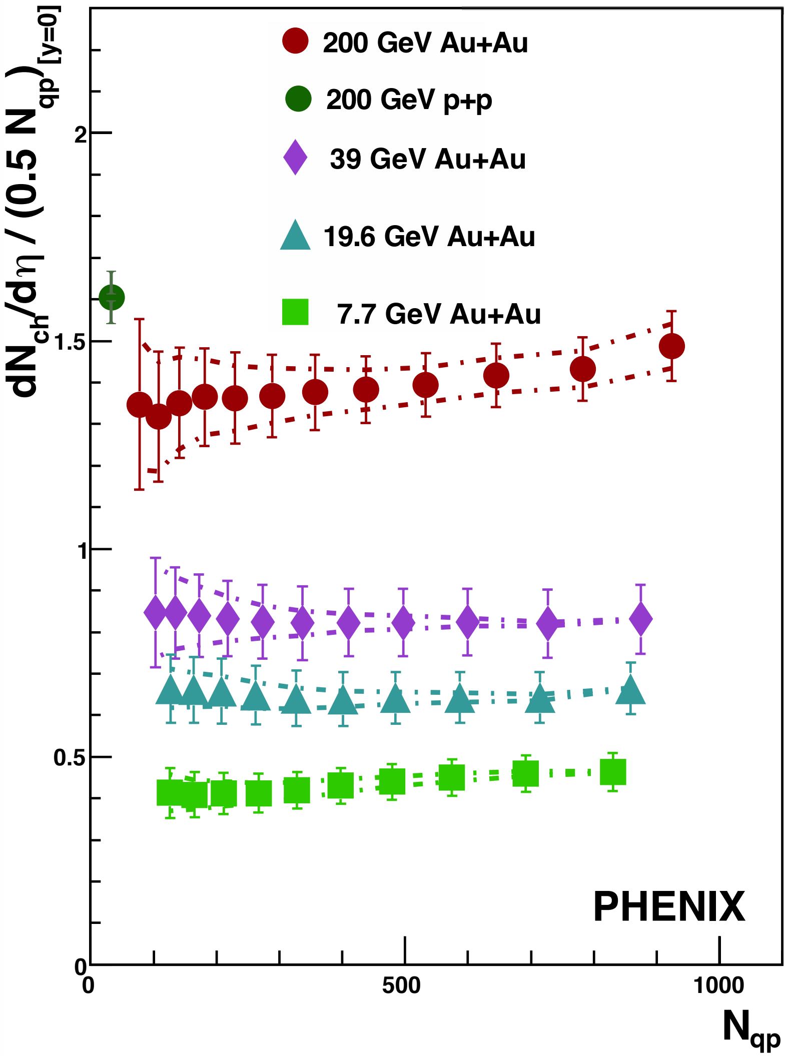
Disagreement from another NQP calculation?



<u>Only from the lowest AuAu point</u>

Of course I noted that they only used our tabulated statistical errors but left out our Type B correlated systematics shown on our plots where **all** the data points can be moved up to the top of their syserror bars with the cost of 1 σ, so that the ratio of the p+p to lowest AuAu point is 1.19±0.17 statistical, or 1.33±0.22 if we simply add the sys and stat in quadrature. i.e. 33±22%≈30% But this difference is not significant.

Disagreement from another NQP calculation? Here is our calculation.



We actually didn't calculate the p+p value in PRC93 (2016) 024901, but did show the systematic errors on the plot. So here they are along with the p+p calculation from PRC93 (2016) 054910 using the same UA5 pbar+p $dN_{ch}/d\eta$ =2.23±0.08 at $\sqrt{s}$=200 GeV with a p+p/Au+Au ratio of 1.19±0.19±0.16 sys i.e. agreement to ≈ 1 σ for all the data points at 200 GeV Au+Au.

As far as I can tell BB&R use r_m=0.94 fm for the proton rms radius in Eq 4 and a gaussian wounding profile for a q+q collision--Not the standard Glauber.

Conclusions

- The Constituent Quark Participant Model (N_{qp}) works at mid-rapidity for A+B collisions in the range (~20 GeV) 39 GeV< $\sqrt{s_{NN}}$< 5.02 TeV.
- Experiments generally all use the same Glauber M.C. but the BB&R's M.C. is different for q+q scattering leading to somewhat different results.
- Attention must be paid to systematic errors.
- How can the event-by-event proton radius variations and quark-quark correlations used in Constituent Quark Glauber models be measured?

Details on "Disagreement" of NQP calculations

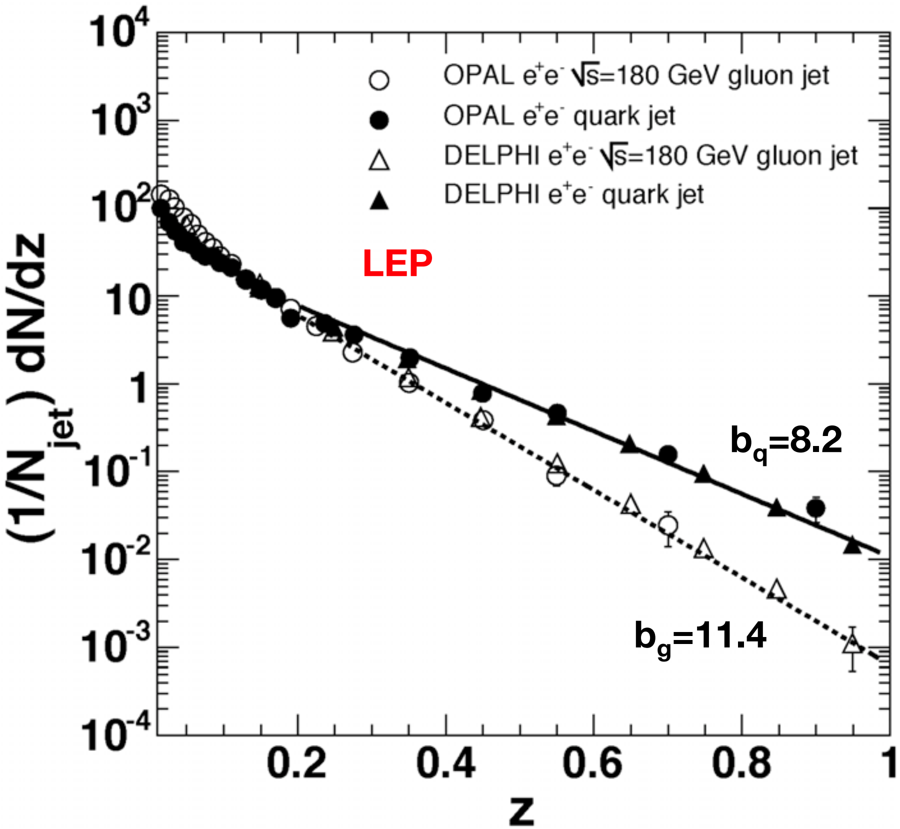
Table 1: $N_{\rm qp}$ in p+p

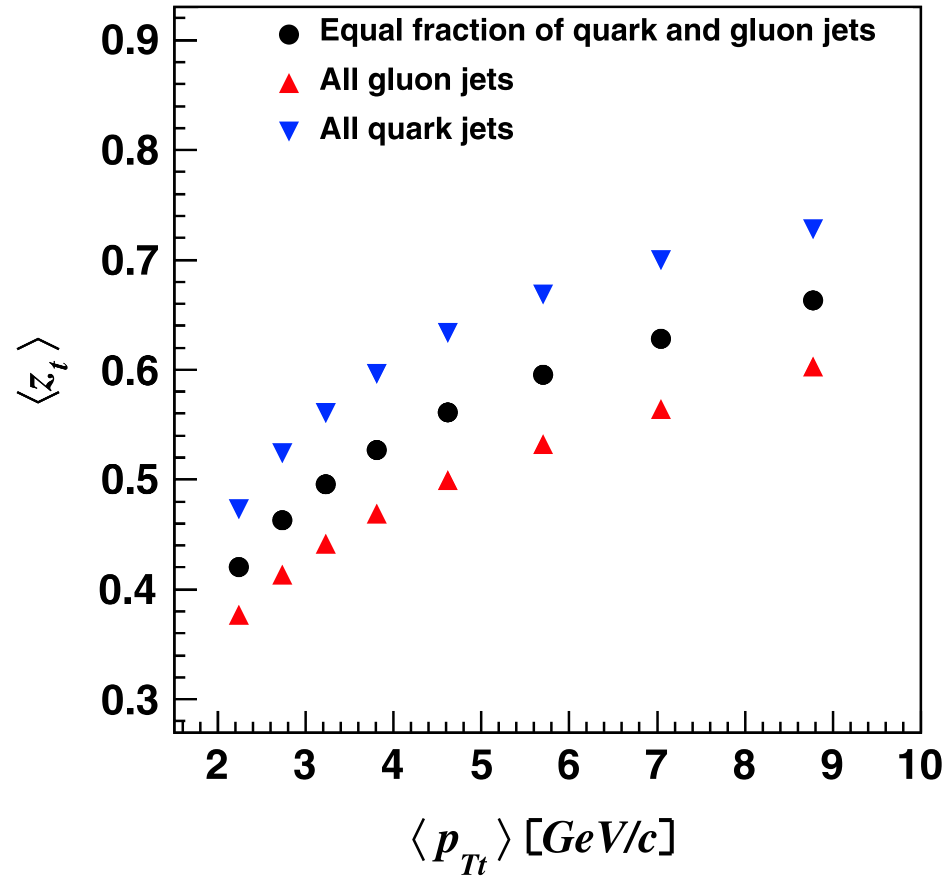
paper	$\sqrt{s_{NN}}$	$\sigma_{nn}^{\rm inel}$	r_m	$\sigma_{qq}^{\rm inel}$ (mb)	$\langle N_{\rm qp}\rangle$
p+p	(GeV)	(mb)	(fm)	(GeV)	
PX2014 Phys. Rev. C**89**, 044905 (2014)	200	42.0	0.81	9.36	2.99
MPTS Phys. Rev. C**93**, 054910 (2016)	200	42.3	0.81	8.17	2.78
Loizides Phys. Rev. C**94**, 024914 (2016)	200	42.	0.81	8.1	2.8
BB&R Phys. Rev. C**94**, 014902 (2016)	200	41.3	0.94	7.0	2.60

reaction	dn/deta	err	sys	QW	err	
p+p Bozek	2.29	0.08		2.6		
p+pMJTBozek	2.23	0.08		2.6		
p+p MPTS	2.23	0.08		2.78		
cent 55-60				QW	err	
AuAu Bozek	52.2	6.5	4.88	80.65		
AuAuPX	52.2	6.5	4.88	77.5	6.8	
	dnch/QW	err				
p+p Bozek	0.881	0.031				
p+pMJTBozek	0.858	0.031				
p+p MPTS	0.802	0.029				
	dnch/QW	stat	sys			
AuAu Bozek	0.647	0.081	0.061			
AuAuPX	0.674	0.103	0.086			
		stat	sys	stat+sys	shift sys	stat
pp/Au Bozek	**1.361**	0.176	0.136	**0.222**	**1.225**	**0.176**
ppmjtB/AuB	**1.325**	0.172	0.133	**0.217**	**1.192**	**0.172**
pp/AuAu PX	**1.191**	0.186	0.159	**0.245**	**1.032**	**0.186**

Appendix
Correlations
Details
For skeptics

B)PHENIX-calculated <z_t> in p+p as a function of p_{Tt} of the trigger using LEP fragmentation functions





PHENIX PRD **74** (2006) 072002, PRD **81** (2010) 012002, give these calculations.
The method is better described in arXiv:nucl-ex/0611008v2 [PoS(CFRNC2006)001]

The away particle p_{Ta} distribution for a given trigger particle p_{Tt} measures the ratio of the away jet to trigger jet p_T $x_E \approx p_{Ta}/p_{Tt}$ (STAR calls z_T)

4.2 The ratio of the away jet to the trigger jet, $\hat{\mathbf{x}}_{\mathbf{h}} = \hat{\mathbf{p}}_{\mathbf{Ta}}/\hat{\mathbf{p}}_{\mathbf{Tt}}$.

$$\left.\frac{dP_\pi}{dx_E}\right|_{p_{T_t}} = N\,(n-1)\frac{1}{\hat{x}_h}\frac{1}{(1+\frac{x_E}{\hat{x}_h})^n}$$

Full derivation next pages
PHENIX π^0 p+p PRD74(2006)072002

2 particle Correlations

$$\frac{d^2\sigma_\pi(\hat{p}_{T_t}, z_t)}{d\hat{p}_{T_t} dz_t} = \frac{d\sigma_q}{d\hat{p}_{T_t}} \times D^q_\pi(z_t)$$

Prob. that you make a jet with $\hat{p}_{Tt}$ which fragments to a π with $z_t=p_{Tt}/\ \hat{p}_{Tt}$

Also detect fragment with $z_a = p_{T_a}/\hat{p}_{T_a}$
from away jet with $\hat{p}_{T_a}/\hat{p}_{T_t} \equiv \hat{x}_h$

$$\frac{d^3\sigma_\pi(\hat{p}_{T_t}, z_t, z_a)}{d\hat{p}_{T_t} dz_t dz_a} = \frac{d\sigma_q}{d\hat{p}_{T_t}} \times D^q_\pi(z_t) \times D^q_\pi(z_a)$$

Prob. that away jet with $\hat{p}_{Ta}$ fragments to a π with $z_a=p_{Ta}/\hat{p}_{Ta}$

$$z_\mathrm{a} = \frac{p_{T\mathrm{a}}}{\hat{p}_{T\mathrm{a}}} = \frac{p_{T\mathrm{a}}}{\hat{x}_\mathrm{h}\hat{p}_{T\mathrm{t}}} = \frac{z_\mathrm{t} p_{T\mathrm{a}}}{\hat{x}_\mathrm{h} p_{T\mathrm{t}}}$$

(1)

$$\boxed{\frac{d\sigma_\pi}{dp_{T_t} dz_t dp_{T_a}} = \frac{1}{\hat{x}_\mathrm{h}\, p_{T_t}} \frac{d\sigma_q}{d(p_{T_t}/z_t)} D^q_\pi(z_t) D^q_\pi\left(\frac{z_t p_{T_a}}{\hat{x}_\mathrm{h} p_{T_t}}\right)}$$

Appears to be sensitive to away jet Frag. Fn.
BUT

I kept going and got a neat result

$$\boxed{\frac{d\sigma_\pi}{dp_{T_t}dz_t dp_{T_a}} = \frac{1}{\hat{x}_h\, p_{T_t}} \frac{d\sigma_q}{d(p_{T_t}/z_t)} D^q_\pi(z_t) D^q_\pi(\frac{z_t p_{T_a}}{\hat{x}_h p_{T_t}})} \qquad (1)$$

Take: $D(z) = B\exp(-bz)$ $\quad \dfrac{d\sigma_q}{d(p_{T_t}/z_t)} = \dfrac{A}{(p_{T_t}/z_t)^{(n-1)}}$

$$(2) \quad \frac{d\sigma_\pi}{dp_{T\mathrm{t}}dp_{T\mathrm{a}}} = \frac{B^2}{\hat{x}_\mathrm{h}} \frac{A}{p^n_{T_t}} \int_{x_{T_t}}^{\hat{x}_\mathrm{h}\frac{p_{T\mathrm{t}}}{p_{T\mathrm{a}}}} dz_\mathrm{t}\, z_\mathrm{t}^{n-1} \exp -bz_\mathrm{t}(1 + \frac{p_{T\mathrm{a}}}{\hat{x}_\mathrm{h} p_{T\mathrm{t}}})$$

$$\frac{d\sigma_\pi}{dp_{T\mathrm{t}}} = \frac{AB}{p^{n-1}_{T_t}} \int_{x_{T_t}}^{1} dz_\mathrm{t}\, z_\mathrm{t}^{n-2} \exp -bz_\mathrm{t}$$

Using: $\Gamma(a,x) \equiv \int_x^\infty t^{a-1}\, e^{-t}\, dt$ Where Γ(a,0)= Γ(a)=(a-1) Γ(a)

The final result

$$\frac{d^2\sigma_\pi}{dp_{T\rm t}dp_{T\rm a}} \approx \frac{\Gamma(n)}{b^n}\frac{B^2}{\hat{x}_{\rm h}}\frac{A}{p_{T_t}^n}\frac{1}{(1+\frac{p_{T\rm a}}{\hat{x}_{\rm h}p_{T\rm t}})^n}$$

$$\frac{d\sigma_\pi}{dp_{T\rm t}} \approx \frac{\Gamma(n-1)}{b^{n-1}}\frac{AB}{p_{T_t}^{n-1}} \quad ,$$

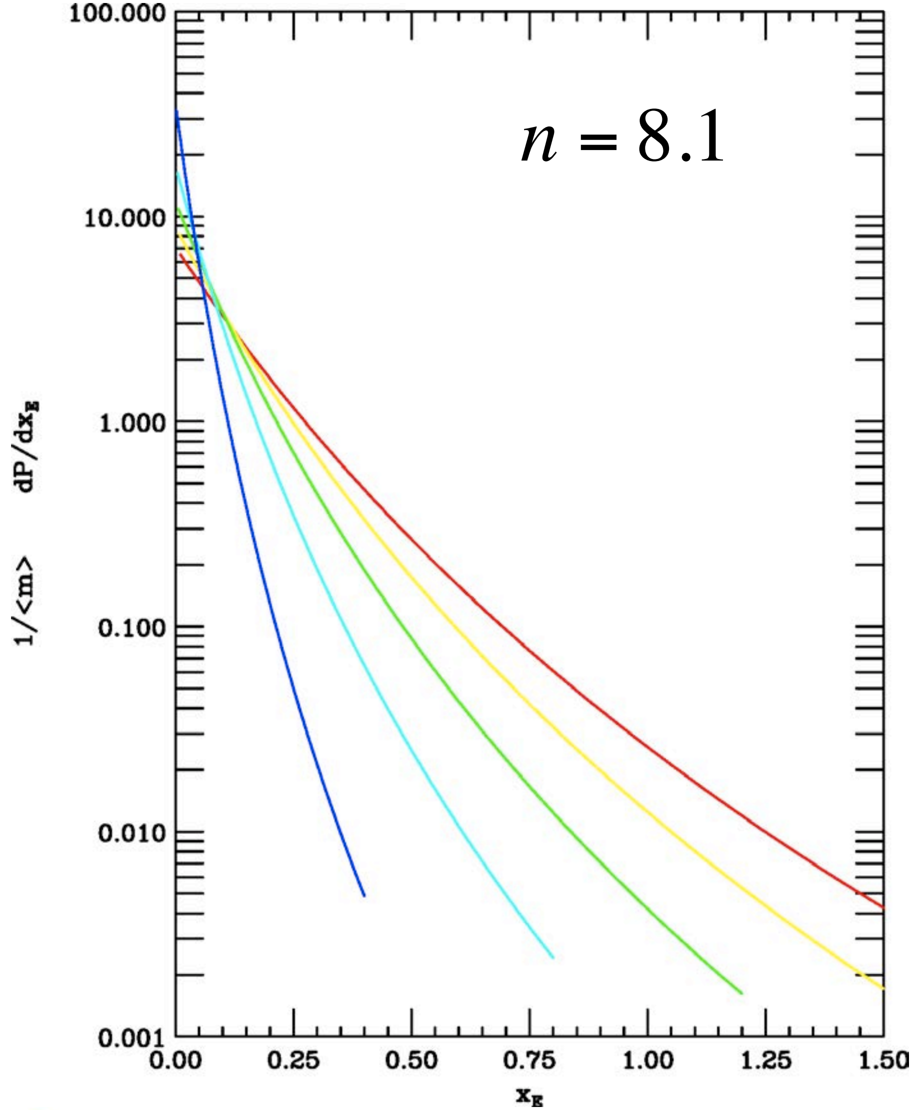
$$\left.\frac{dP_\pi}{dp_{T\rm a}}\right|_{p_{T\rm t}} \approx \frac{B(n-1)}{bp_{T\rm t}}\frac{1}{\hat{x}_{\rm h}}\frac{1}{(1+\frac{p_{T\rm a}}{\hat{x}_{\rm h}p_{T\rm t}})^n} \quad . \qquad (42)$$

In the collinear limit, where $p_{T\rm a}=x_{\rm E}p_{T\rm t}$:

$$\left.\frac{dP_\pi}{dx_{\rm E}}\right|_{p_{T\rm t}} \approx \frac{B(n-1)}{b}\frac{1}{\hat{x}_{\rm h}}\frac{1}{(1+\frac{x_E}{\hat{x}_{\rm h}})^n} \quad . \qquad (43)$$

Where B/b≈<m>≈b is the mean charged multiplicity in the jet

Shape of x_E distribution depends on $\hat{x}_h$ and n but not on b



$\hat{x}_h$

1.0

0.8

0.6

0.4

0.2

Why dependence on the Frag. Fn. vanishes

- The only dependence on the fragmentation function is in the normalization constant B/b which equals <m>, the mean multiplicity in the away jet from the integral of the fragmentation function.

- The dominant term in the x_E distribution is the Hagedorn function $1/(1 + x_E/\hat{x}_h)^n$ so that at fixed p_{Tt} the x_E distribution is predominantly a function only of x_E and thus exhibits x_E scaling, as observed.

- The reason that the x_E distribution is not sensitive to the shape of the fragmentation function is that the integral over z_t in (1, 2) for fixed p_{Tt} and p_{Ta} is actually an integral over jet transverse momentum $\hat{p}_{T_t}$. However since the trigger and away jets are always roughly equal and opposite in transverse momentum (in p+p), integrating over $\hat{p}_{T_t}$ simultaneously integrates over $\hat{p}_{T_a}$. The integral is over z_t, which appears in both trigger and away side fragmentation functions in (1).